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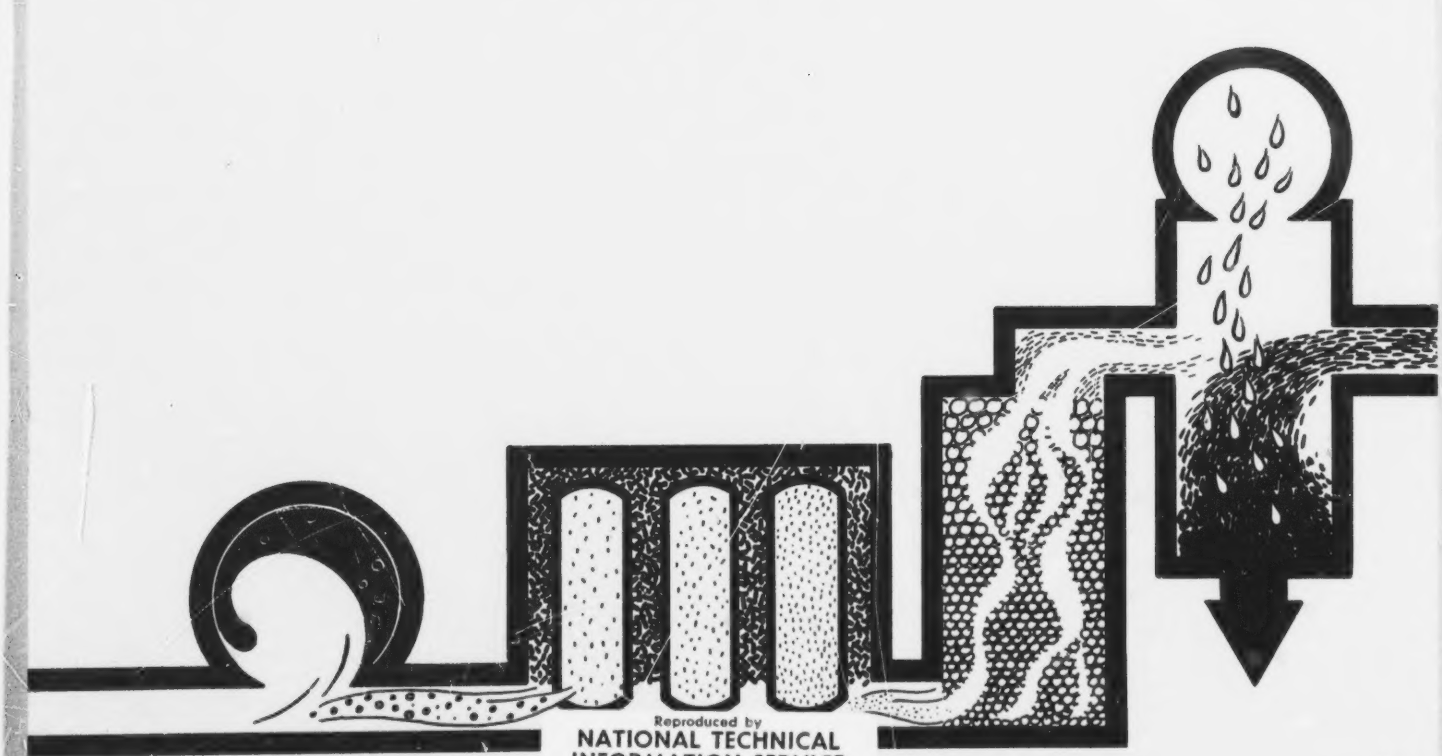

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SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

1. Report No.

2.

3. Accession No.

W 72-09386

4. Title

WASTE TREATMENT LAGOONS-STATE OF THE ART,

5. Report Date

6\.

8. Performing Organization Report No.

7. Author(s)

[redacted]
[redacted]
[redacted]

10. Project No.

EPA, 17090 EHX 07/71
Program

9. Organization

Missouri Basin Engineering Health Council,
Cheyenne, Wyoming

11. Contract/Grant No.

13. Type of Report and Period Covered

12. Sponsoring Organization Environmental Protection Agency

15. Supplementary Notes

Water Pollution Control Research Series [redacted], July 1971, 152 p., 9 tab, 42 ref.

16. Abstract

A review of published literature and field evaluations revealed the presence of over 3500 waste treatment lagoons currently in operation in the United States. The three types of lagoons in use include: (1) oxidation lagoons; (2) aerated lagoons, and (3) anaerobic lagoons. Oxidation lagoons depend upon algae to supply oxygen by photosynthesis and degrade the waste products. Effluent quality is determined by the quantity of algae in the effluent and several methods of algae removal are currently under investigation. Aerated lagoons may be merely oxidation ponds with supplemental aeration, partially mixed activated sludge (facultative aerated) or complete mix activated sludge (CMAS) systems. High quality effluents from aerated lagoons can be achieved only by removing effluent microbial solids. Anaerobic lagoons can provide up to 80% BOD removals, but must be followed by some type of aerobic treatment to produce a high quality effluent. This review has demonstrated that lagoons do have applicability to the total waste treatment problem, but the future of lagoons depends upon proper design and operation in relationship with the fundamental biochemistry of the microbes in the various systems. (Lowry-Texas)

17a. Descriptors

*Sewage lagoons, *Aerated lagoons, *Oxidation lagoons, *Design criteria, Biodegradation, Algae, Photosynthesis, Suspended solids, Separation techniques, Filtration, Municipal wastes, Industrial wastes, Operation and maintenance, *Waste water treatment, Water quality control, *Reviews

17b. Identifiers

*Facultative lagoons, *Anaerobic lagoons,

17c. COWRR Field & Group

05D, 10F

Copy available from GPO Sup Doc
[redacted] , $1.25 ; microfiche
from NTIS as PB 207937, $0.95.

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages

22. Price

Send To:

WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

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WASTE TREATMENT LAGOONS - STATE OF THE ART

by

Missouri Basin Engineering Health Council
State Office Building
Cheyenne, Wyoming

for the
Office of Research and Monitoring
ENVIRONMENTAL PROTECTION AGENCY

Project #17090 EHX

July, 1971

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 - Price $1.25

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ABSTRACT

Waste treatment lagoons have found extensive use in the United States with over 3500 units in operation. For convenience, it was possible to break down waste treatment lagoons into three groups: (1) oxidation ponds, (2) aerated lagoons and (3) anaerobic lagoons.

Oxidation ponds are relatively shallow lagoons with a long retention period. Operating data indicate that oxidation ponds do not produce a high quality effluent all of the time. The effluent quality problem is created by algae which are discharged in the effluent. Multicell series ponds improve effluent quality significantly. Various types of simple filters may be of value but further research is needed.

Aerated lagoons were developed to meet overloaded oxidation ponds by supplying oxygen mechanically. The aerated lagoons have developed as short retention time, completely mixed activated sludge systems and as large, incompletely mixed systems. The CMAS aerated lagoons lend themselves to mathematical evaluation and more precise design whereas incompletely aerated lagoons defy simple evaluation. Aerated lagoons must be modified to obtain maximum solids removal if a high quality effluent is to be obtained.

Anaerobic lagoons are heavily loaded systems which depend on anaerobic metabolism to produce up to 80% BOD reduction. The key to good anaerobic systems lie in adequate mixing below the surface, surface scum, warm temperature, sufficient retention time, and a uniform rate of feeding. To date best results with anaerobic lagoons have been obtained with meat packing wastes. Aerobic treatment must follow anaerobic lagoons in order to produce a high quality effluent.

The future of wastewater lagoons lies with their proper design and operation. There is no reason to believe lagoons cannot meet water quality criteria with minor modifications.

This report was submitted in fulfillment of Project # 17090EHX under the sponsorship of the Environmental Protection Agency.

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SECTION I
CONCLUSIONS

1. Operational data from oxidation ponds indicates that effluent quality will not meet current Water Quality Criteria all of the time.

2. Effluent quality from oxidation ponds is determined by the concentration of algae in the effluent.

3. Single cell ponds are not as efficient as multicell ponds in reducing the suspended algae concentration.

4. Chemical precipitation can be used to remove the excess algae from the effluent but is expensive.

5. Research indicates a rock filter may assist in removal of algae.

6. Coliform reductions in oxidation ponds are the result of starvation rather than from toxic materials or from unusual predation.

7. Aerated lagoons are basically useful for partial BOD removal.

8. High quality aerated lagoon effluents can be produced only if the microbial solids are removed from the effluents.

9. Low temperatures adversely affect floating aerators in aerated lagoons with ice build up changing the operating characteristics.

10. Diffused aeration systems have worked better than mechanical systems in cold climates.

11. Completely mixed aerated lagoons require short term aeration time for economical operation.

12. Facultative aerated lagoons are designed with enough aeration to supply the oxygen demand but not enough to keep the solids in suspension.

13. Performance criteria cannot be predicted for facultative aerated lagoons prior to actual operation.

14. Aerated oxidation ponds are overloaded oxidation ponds to which diffused air was added to increase algae growth.

15. Anaerobic lagoons are useful in reducing the BOD up to 80% with concentrated organic wastes.

16. Anaerobic lagoons must be followed by aerobic treatment for a high quality effluent.

17. Anaerobic lagoons have been most successful in treating meat packing wastes.

18. The future of all types of lagoons depends upon proper design and operation in relationship with the fundamental biochemistry of the microbes in the various systems.

SECTION II

RECOMMENDATIONS

This study was designed to review the current state of knowledge concerning wastewater lagoons and to summarize the existing information on design and operation as well as indicating future needs in order to improve these systems.

One of the primary needs for all three wastewater lagoon systems is for a concerted field data gathering and evaluation program. The simplicity of wastewater lagoons has resulted in little operational data of value for proper engineering evaluation. Long term data collection is an urgent need that should be started immediately if information is to be obtained in the forseeable future.

Solids separation studies should be begun immediately since the primary cause of poor effluent quality is directly related to the microbial solids in the effluent. Multicell ponds and rock filters offer two possible methods for removing the solids to a reasonable level.

Wastewater lagoons have been an important part of the waste treatment package, especially for small municipalities and industries. It is apparent that current design criteria for wastewater lagoons are not adequate to meet the water quality criteria currently being established. As a net result, there is some effort being made to discard wastewater lagoons from future consideration. Fundamental concepts discussed in this study point to a number of ways wastewater lagoon designs can be modified to produce the desired effluent quality. The value of wastewater lagoons far outweighs their disadvantages, making it essential that efforts be directed to demonstrating how the different lagoons systems can be modified to produce the desired results.

SECTION III

INTRODUCTION

Although waste treatment lagoons were first used in the mid-twenties, it was not until the last two decades that waste treatment lagoons achieved popularity. Currently, there are over 3500 waste treatment lagoons handling domestic sewage in the United States and more are being constructed each day. In spite of their widespread use, there is limited data as to the operational characteristics of waste treatment lagoons. Engineers have not bothered to make scienfific evaluations to correlate operational conditions with original design criteria. Only in a few instances has there been the development of basic data sufficient to produce sound design criteria. While there has been a large number of studies in waste treatment lagoons, most of these studies have been fragmented and lacking in sufficient depth to have real meaning. If we are to continue to design and construct waste treatment lagoons, it is important that we have proper design criteria that will result in the production of the desired effluent quality. The purpose of this state of the art review is to bring as much information as is available together to develop sound design and operational criteria. It is hoped that this review will be of value to all engineers concerned with waste treatment lagoons.

One of the problems with waste treatment lagoons is that of semantics. Over the years a number of terms have been used to designate waste treatment lagoons. Each person selected the term that was used in his area. The net result has been a certain amount of confusion. To compound the problem, two additional modifications of the original waste treatment lagoon have been developed with conflicting terminology. In order to eliminate some of the confusion with regard to nomenclature, it was decided to use the following terms to describe the different waste treatment lagoons:

1. Oxidation Ponds: the original waste treatment lagoon utilizing bacteria-algae symbiosis and sedimentation for treatment.
2. Aerated Lagoons: waste treatment lagoons having a mechanical aeration device to supply the oxygen needed by the bacteria for stabilization.
3. Anaerobic Lagoons: waste treatment lagoons devoid of oxygen, utilizing methane bacteria for stabilizing the organic matter in the wastes.

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These definitions were not meant to be all inclusive; but rather were designed to define the three basic modifications of waste treatment lagoons in simple terms that could be meaningful to engineers concerned with their design and operation.

Each of the three basic waste treatment lagoon systems has their own distinctive characteristics even though they all operate on the same fundamental biochemical concepts. In order to minimize confusion, it was decided to divide the State of the Art review into three distinct sections, one for each of the three basic lagoon systems. This organizational scheme resulted in some overlap of fundamental ideas; but it was felt that this limited redundancy would help reinforce the fundamental concepts. In view of the different backgrounds of the authors, the approaches to each section represent three ways of looking at waste treatment lagoons. At the same time it should be recognized that the senior author exercised his prerogative of assisting the junior authors with their sections. Most of all one should understand that this State of the Art review was not prepared by three university professors from a purely academic point of view. All three of the authors have been actively involved in field studies as well as in laboratory studies. This State of the Art reflects their professional experience both directly and indirectly through interpretation of other investigators research results. The value of this review lies in the fact that it is more than just a compilation of published information, it is a professional interpretation and critical evaluation of the available literature. Judgement has been used in selecting the references from the tremendous number of reports and publications. Some information was missed by oversight; while other information was omitted for lack of specific value. In any case, the authors recognize that some people will disagree with their selection and interpretation. For this the authors offer no apology as no personal slight was intended. Each of us has assumed full professional responsibility for what we have written and we believe that we have shown that waste treatment lagoons have just begun to find their place in preserving our environment from pollution. At the same time, we recognize the need for modification of existing engineering practice if we are to achieve the maximum capabilities of waste treatment lagoons. We have attempted to point out the areas where changes are needed and we have made specific recommendations. Ours was not just the role of the critic, but that of the innovator as well. We hope that you will find this State of the Art of real value. If you do, then our efforts will have been well spent.

SECTION IV

OXIDATION PONDS

Oxidation ponds grew out of the concept of natural purification. It was observed that the discharge of wastewaters into streams and rivers resulted in the purification of the organic contaminants by the microorganisms living within the streams. Only a short time of flow was required to stabilize relatively large quantities of organic pollutants. Not only was the organic matter stabilized but the enteric pathogens died off, making the water safe for reuse downstream. As the need for wastewater treatment increased, it was recognized that simple systems requiring little operational skills were needed for small communities, shopping centers, motels, subdivisions, and individual homes. Existing wastewater treatment systems utilized the principles of natural purification but required considerable equipment and close operational controls. Since the basic problem in the stabilization of organic wastes was the transfer of oxygen from the atmosphere into the wastewaters, it was only natural to create a shallow lake to permit rapid transfer of oxygen for the microorganisms. The large surface area permitted oxygen to penetrate the shallow liquid depth, thereby stimulating aerobic bacteria and preventing odor nuisances from developing. It was soon observed that these shallow sewage ponds stimulated the growth of algae during warm weather with the production of tremendous quantities of oxygen. It was soon concluded that the bacteria and algae in the oxidation ponds formed a symbiotic relationship which accelerated the treatment of wastewaters. The bacteria aerobically stabilized the organic matter with the release of carbon dioxide which was taken up by the algae in the presence of sunlight with the production of more algae and the release of oxygen for the bacteria. Together the bacteria and the algae produced a combined reaction that neither produced alone. The resulting effluent from these sewage ponds showed a definite BOD reduction and contained only dispersed green algae. Thus, the oxidation pond found application as the simplest biological treatment system to design, construct, and operate; as long as land was available.

Initially, oxidation ponds were used after primary sedimentation to remove gross solids; but it was soon learned that raw sewage could be added directly to the oxidation pond without any problems. Design of oxidation ponds was largely a matter of trial and error. Data learned from existing plants were incorporated into the design of new plants. As additional experience was gained in the field, the design of oxidation ponds became more sophisticated. California and

Texas were the first states to develop design criteria for oxidation ponds. World War II showed the results that could be obtained in treating sewage from military camps and furnished the impetus to look at oxidation ponds more seriously. Slowly but surely, sound design criteria were developed which could be applied almost everywhere in the United States.

DESIGN CRITERIA

Originally, the design criteria for oxidation ponds was relatively simple. Domestic sewage oxidation ponds were designed for 20 to 25 days retention based on settled effluent. Using 100 gpcd flow rates and a 3 ft. depth, loading rates up to 400 people per acre of 45 lbs BOD/acre/day were allowed. Two or more ponds were recommended. These criteria were the basis of design of oxidation ponds in California by Caldwell (1).

Today, most state health departments have more detailed design criteria. By and large these design criteria have been developed from the Committee Report of the Missouri Basin Engineering Health Council (2), approved on January 21, 1960. The Recommended Standards for Sewage Works, Great Lakes-Upper Mississippi River Board of State Sanitary Engineers, 1969 Edition, represents the typical design criteria currently being employed by engineers in the design of oxidation ponds. The following design criteria was reproduced from material submitted by the South Dakota State Department of Health.

WASTE STABILIZATION PONDS (Lagoons)

A. Supplement to Engineer's Report

The engineer's report shall contain pertinent information on location, geology, soil conditions, area for expansion, and any other factors that will affect the feasibility and acceptability of the proposed treatment.

The following information must be submitted in addition to that required in Section I, engineer's report.

1. Supplementary Field Survey Data

a. The location and direction of all residences, commercial development, and water supplies within 1/2 mile of the proposed pond.

b. Soil borings to determine surface and subsurface soil characteristics of the immediate area and their effect on the construction and operation of a pond located on the site.

c. Data demonstrating anticipated percolation rates at the elevation of the proposed pond bottom.

d. A description, including maps showing elevations and contours of the site and adjacent area suitable for expansion.

e. Sulfate content of the basic water supply.

B. Basis of Design

1. Area and Loadings

One acre of water surface should be provided for each 100 design population or population equivalent. In terms of BOD, a loading of 0.4 pounds per day per 1,000 square feet should not be exceeded. Higher design loadings will be judged after review of material contained in the engineer's report and after a field investigation of the proposed site by the reviewing authority.

Due consideration will be given to possible future municipal expansion and/or additional sources of wastes when the original land acquisition is made. Suitable land should be available at the site for increasing the size of the original construction.

2. Industrial Wastes

Due consideration will be given to the type and effects of industrial wastes on the treatment process.

3. Multiple Units

Multiple cells designed to permit both series and parallel operation are recommended for all except small installations (3 acres or less). All future stabilization pond designs should specify two-cell units or, on small installations, two-level bottoms. This flexibility is desirable when loadings are light or when a community is installing a new sewer system, since in the period preceding substantial connections the entire discharge can be put into a single cell, thus facilitating the maintenance of satisfactory water levels. In addition, when a low algae content in the effluent is desired, the cells may be advantageously operated in parallel during fall, winter, and spring when algae development is less intensive and in series during the summer months. Series operation is also beneficial where a high level of BOD or coliform removal is important.

Where a greater degree of treatment is necessary or desirable, 1 or more cells in each series may be added to the primary cell. In series operation, the primary cell shall have a surface area equal to that set forth in Section B.1.

4. Pretreatment

When ponds are used to provide additional treatment for effluents from existing or new primary or secondary sewage treatment works, the reviewing authority will, upon request, establish BOD loadings for the pond after due consideration of the efficiencies of the preceding treatment units.

5. Pond Shape

The shape of all cells should be such that there are no narrow or elongated portions. Round, square, or rectangular ponds with a length not exceeding 3 times the width are considered most desirable. No islands, peninsulas, or coves should be permitted. Dikes should be rounded at corners to minimize accumulations of floating materials.

C. Location

1. Distance From Habitation

A pond site should be as far as practicable from habitation or any area which may be built up within a reasonable future period.

2. Prevailing Winds

If practicable, ponds should be located so that local prevailing winds will be in the direction of uninhabited areas. Preference should be given sites which will permit an unobstructed wind sweep across the ponds, especially in the direction of the local prevailing winds.

3. Surface Runoff

Location of ponds in watersheds receiving significant amounts of runoff water is discouraged unless adequate provisions are made to divert storm water around the ponds and otherwise protect pond embankments.

4. Ground Water Pollution

Proximity of ponds to water supplies and other facilities subject to contamination and location in areas of porous soils and fissured rock formations should be critically evaluated to avoid creation of health hazards or other undesirable conditions. The possibility of chemical pollution may merit appropriate consideration.

D. Pond Construction Details

1. Embankments and Dikes

a. Material

Embankments and dikes shall be constructed of relatively imprevious materials and compacted sufficiently to form a stable structure. Vegetation should be removed from the area upon which the embankment is to be placed.

b. Top Width

The minimum embankment top width should be 8 feet to permit access of maintenance vehicles. Lesser top widths will be considered for very small installations, 1 acre or less.

c. Maximum slopes

Embankment slopes should not be steeper than:

(1) Inner
3 horizontal to 1 vertical

(2) Outer
3 horizontal to 1 vertical.

d. Minimum Slopes

Embankment slopes should not be flatter than:

(1) Inner
6 horizontal to 1 vertical. Flatter slopes are sometimes specified for larger installations because of wave action but have the disadvantage of added shallow areas conducive to emergent vegetation.

(2) Outer
Not applicable, except significant volumes of surface water should not enter the ponds.

e. Freeboard

Minimum freeboard shall be 3 feet except for very small installations, 1 acre or less.

f. Minimum Depth

The minimum normal liquid depth should be 2 feet.

g. Maximum Depth

Maximum normal liquid depth should be 5 feet.

h. Seeding

Embankments shall be seeded from the outside toe to 1 foot above the high water line on the dikes, measured on the slope. Perennial type, low growing, spreading grasses that withstand errosion and can be kept mowed are most satisfactory for seeding of embankments. In general, alfalfa and other long-rooted crops should not be used in seeding, since the roots of this type plant are apt to impair the water holding efficiency of the dikes. The County Agricultural Extension Agent can usually advise as to hardy, locally suited permanent grasses which would be satisfactory for embankment seeding. Additional protection for embankments (riprap) may be necessary where the dikes are subject to erosion due to severe flooding of an adjacent watercourse or severe wave action.

i. Vegetation Control

A method shall be specified which will prevent vegetation growth over the bottom of the lagoon and up to 1 foot above the water line on the dikes.

2. Pond Bottom

a. Uniformity

The pond bottom should be as level as possible at all points. Finished elevations should not be more than 3 inches from the average elevation of the bottom. Shallow or feathering fringe areas usually result in locally unsatisfactory conditions.

b. Vegetation

The bottom shall be cleared of vegetation and debris. Organic material thus removed shall not be used in the dike core construction. However, suitable topsoil relatively free of debris may be used as cover material on the outer slopes of the embankment.

c. Soil Formation

The soil formation or structure of the bottom should be relatively tight to avoid excessive liquid loss due to percolation or seepage. Soil borings and tests to determine the characteristics of surface soil and subsoil shall be made a part of preliminary surveys to select pond sites. Gravel and limestone areas must be avoided.

d. Percolation

The ability to maintain a satisfactory water level in the ponds is one of the most important aspects of design. Removal of porous topsoil and proper compaction of subsoil improve the waterholding characteristics of the bottom. Removal of porous areas, as gravel or sandy pockets, and replacement with well-compacted clay or other suitable material may be indicated. Where excessive percolation is anticipated, sealing of the bottom with a clay blanket, bentonite, or other sealing material should be given consideration.

3. Influent Lines

a. Material

Any generally accepted material for underground sewer construction will be given consideration for the influent line to the pond. The material selected should be adapted to local conditions. Special consideration must be given to the character of the wastes, possibility of septicity, exceptionally heavy external loadings, abrasion, the necessity of reducing the number of joints, soft foundations, and similar problems. Surcharging of the sewer upstream from the inlet manhole is not permitted.

b. Manholes

A manhole shall be installed at the terminus of the outfall line or the force main and shall be located as close to the dike as topography permits and its invert should be at least 6 inches above the maximum operating level of the pond to provide sufficient hydraulic head without surcharging the manhole.

c. Influent Lines

Influent lines should be located along the bottom of the pond so that the top of the pipe is just below the average elevation of the pond bottom. This line can be placed at zero grade. The use of an exposed dike to carry the influent line to the discharge points is prohibited, as such a structure will impede circulation.

d. Point of Discharge

The influent line to a single celled pond should be essentially center discharging. Each cell of a multiple celled pond operated in parallel shall have its own near center inlet but this does not apply to those cells following the primary cell when series operation alone is used. Influent lines or interconnecting piping to secondary cells of multiple celled ponds operated in series may consist of pipes through the separating dikes. (Section D.4.c.) Influent lines to rectangular ponds should terminate at approximately the third point fartherest from the outlet structure. Influent and effluent piping should be located to minimize short-circuiting within the pond.

e. Inlets

The inlet line shall discharge horizontally into a shallow, saucer-shaped depression which should extend below the pond bottom not more than the diameter of the influent pipe plus 1 foot.

f. Discharge Apron

The end of the discharge line should rest on a suitable concrete apron with a minimum size of 4 feet square.

4. Overflow Structures and Interconnecting Piping

a. Material

Interconnecting piping and overflows should be of cast iron pipe or corrugated metal pipe of ample size.

b. Overflow Structure

Overflow structures should consist of a manhole or box equipped with multiple-valved pond drawoff lines or an adjustable overflow device so that the liquid level of the pond can be adjusted to permit operation at depths of 2 to 5 feet. The lowest of the drawoff lines to such structure should be 12 inches off the bottom to control eroding velocities and avoid pickup of bottom deposits. The overflow from the pond during ice-free periods should be taken near, but below, the water surface to release the best effluent and insure retention of floating solids. The structure should also have provisions for draining the ponds. A locking device should be provided to prevent unauthorized access to the level control facilities. When possible the outlet structure should be located on the windward side to prevent short-circuiting. Consideration must be given in the design of all structures to protect against freezing or ice damage under winter conditions.

c. Interconnecting Piping

Interconnecting piping for multiple unit installations operated in series should be valved or provided with other arrangements to regulate flow between structures and permit flexible depth control. The interconnecting pipe to the secondary cell should discharge horizontally near the lagoon bottom to minimize need for erosion control measures and should be located as near the dividing dike as construction permits.

E. Miscellaneous

1. Fencing

The pond area shall be enclosed with a suitable fence to exclude livestock and discourage trespassing. A vehicle access gate of minimum 8 foot width to accomodate mowing equipment should be provided. All access gates should be provided with locks.

2. Warning Signs

   Appropriate signs should be provided along the fence around the pond to designate the nature of the facility and advise against trespassing. A minimum size of 20" by 12" with a minimum size letter of 2" is recommended.

3. Flow Measurement

   Provisions for flow measurement shall be provided on the inlet and outlet.

4. Liquid Depth Operation

   Optimum liquid depth is influenced to some extent by lagoon area since circulation in larger installations permits greater liquid depth. The basic plan of operation may also influence depth. Facilities to permit operation at selected depths between 2 and 5 feet are recommended for operational flexibility.

Intrepretation of Criteria

Oxidation ponds have been considered as the equivalent to other secondary treatment systems. Operational data have indicated 99 percent MPN coliform reduction and BOD reductions from 70 percent in the winter under ice cover to 99 percent in the summer. This degree of treatment combined with their simplicity has been responsible for the widespread use of oxidation ponds.

Loading

Because of the importance of light for the growth of algae and the concept of bacteria-algae symbiosis, loading criteria have been based on the needs of the algae. Oxidation ponds have large surface areas to give maximum exposure to the sunlight. The loading factors have been given in terms of population per acre or in terms of BOD per acre per day. The previous design criteria indicated one acre of oxidation pond surface for each 100 population. Further south in Oklahoma the loading rate can be increased to one acre per 200 population. The use of population loading rates is based on typical domestic sewage where BOD data are not available. The BOD loading was 0.4 lbs/1000 sq.ft./day or 17.4 lbs/acre/day. Further south in Missouri the BOD loading can be 45 lbs/acre/day. While it may seem that these surface loadings are rather arbitrary, there is a definite basis for these loadings utilizing the available light for photosynthesis. Oswald and Gotaas (3) discussed the relationship between bacterial oxygen demand and photosynthesis meeting this demand. They indicated that photosynthetic efficiencies of only 10 percent were possible in sewage oxidation ponds. Neel *et al* (4) suggested 1.5 langleys (1 langley = 1 gm cal. per cm^2)/day/lb BOD/acre was required for proper operation of oxidation ponds where ice was not a factor in the winter months. Winter loadings cannot be evaluated from a light viewpoint and must be based on experience. They found that 20 lbs BOD/acre/day was the practical winter loading rate. Although light was believed to be a critical design factor, engineers were unable to utilize the design equations employing light variations effectively. Since light and load conditions were interrelated, BOD loading factors could be employed more easily with decreasing loading rates as one progressed from south to north.

Number of Ponds.

Multiple ponds have been recommended from the very beginning. Two ponds in series were considered as minimum. In Sweden, Wennstrom (6) constructed a system in 1934 with three oxidation ponds in series and added the fourth pond in 1939. During the summer months microscopic animals developed which ate the excess algae in Pond 4. Even without the development of microscopic animals, multiple cell oxidation ponds produced an effluent with less algae than single cell ponds. Unfortunately, engineers have tended to ignore the value of multiple cell ponds and have constructed single cell ponds. The report of the Missouri Basin Engineering Health Council (2) may have contributed to the shift to single cell ponds by stating that single cell ponds were better for small installations. Since single cell ponds were easier to construct than multiple cell ponds, most oxidation pond installations were considered small. The net result has been that a large number of oxidation ponds are not producing the effluent quality that they should be producing. A short time ago Oswald et al (7) developed an integrated oxidation pond system with sound subdivision planning in which he recommendeded six ponds in series. The effluent quality in the last pond was such that it could be used in a park without danger.

Shape

It is interesting to note that shape is important in the design of oxidation ponds. The suggested design criteria recommend round, square, or slightly rectangular ponds. The purpose of this design is to permit distribution of the incoming load throughout the pond, depending upon wind direction. The shape of the oxidation pond probably is not as important as originally thought. A study in Israel (8) has shown that it is possible to have a long narrow oxidation pond to create plug flow characteristics. It was found that the long narrow type pond gave the same results as the square type pond. As long as reasonable attention is paid to the prevailing winds and their effect on pond mixing, the shape of the pond is not critical.

Location

The location of oxidation ponds should be as far from houses as possible so that odor nuisances do not create problems. It should be recognized that future growth will encroach on any waste treatment plant. There is no way to design a treatment plant that will remain isolated forever. This is one of the reasons why conservative design criteria should be employed to minimize the possibility of odor nuisances. Care should be made that the prevailing winds blow away from the community served as they pass over the oxidation pond. This will minimize the public complaints about the sewage treatment plant. It is also important that the pond surface be free of obstructions so that the wind produces maximum mixing. Surrounding the oxidation pond by tall trees may hide the pond from view as might location in a ravine; but wind action will be diverted above the pond and mixing will be minimized. Without adequate mixing, the oxidation pond will not function properly. It is necessary to divert surface runoff from entering the treatment plant. Too much surface runoff will reduce the retention time below desirable levels. It is relatively simple to divert surface drainage around the pond into the final effluent. Care should be taken to insure that ground waters near the ponds are not contaminated. Soil percolation tests can show the ability of the soil to hold the water. Neel and Hopkins (9) documented an excellent example of an oxidation pond built in porous soil. Seepage was so great that the pond was filled with difficulty and nearby water wells became contaminated with synthetic detergents. This study clearly demonstrated the value of sealing ponds prior to operation. Clay has been used to seal ponds as has plastic lining. The organics in the wastewaters cannot be counted on to seal the pond as there is simply not enough organic matter for a complete seal for many years in most raw sewage oxidation ponds. Evaporation is important in some areas of the United States. Where a zero effluent discharge system is desired, evaporation and percolation must balance the influent flow and precipitation. In arid areas, evaporation may necessitate deeper pond depths during the driest period of the year. Because of evaporation and percolation it is desirable to provide flow measuring devices at the influent as well as at the effluent. Too few plants have provided even the simplest measuring devices, preventing any reasonable evaluation of the treatment plant operations.

Depth

The liquid depth control in oxidation ponds should be variable between a minimum of 2 ft and a maximum of 5 ft, except in special circumstances where evaporation is very high. Normal pond depth is 4 ft. This permits reasonable mixing of the oxygenated upper layer of water with the deoxygenated lower water layers so that aerobic conditions can be maintained in the pond. Where winter conditions are severe, the oxidation pond merely becomes a sewage storage tank until warm weather arrives. At low temperatures biological activity is reduced to a minimum and the sewage remains essentially untreated until spring. For this reason the ponds are normally drawn down to 2 ft after the first frost has killed the algae. The effluent of the pond volume without any water quality problems. This leaves 3 ft of pond depth for storage of sewage during the winter months before any discharge occurs. Discharge can be made in the spring when effluent quality meets water quality criteria. The shallow pond then yields maximum treatment as the liquid warms and normal depth can be reset without serious problems. Where severe winters are not a problem, the depth of the pond is kept constant at all times, adjustable water depths are not of real value under these conditions and can be ignored.

The operation of oxidation ponds is affected by many factors such as the waste characteristics, available light, temperature, wind, depth, retention time, and microbial predomination. The design criteria established to date attempts to produce the optimum system. The success or failure of the design criteria is determined by the quality of the effluent produced daily in the field. In order to evaluate existing design criteria it is necessary to examine the field experiences that have been reported for oxidation ponds and to determine the critical variations effecting design.

OPERATING EXPERIENCES

Domestic Sewage

In the early part of the 1950s oxidation ponds were beginning to see extensive use in the Missouri River Basin for the treatment of domestic sewage except that little real information was available as to a scientific evaluation of their operations. In 1954 the Conference of State and Territorial Health Officers requested that the USPHS make detailed studies on oxidation ponds so that sound design and operational data could be developed. Prior to this request, the primary data on oxidation ponds came from Caldwell (1). In working with oxidation ponds Caldwell had developed some definite design and operational concepts. He believed that only settled sewage should be used in oxidation ponds. With settled sewage satisfactory treatment could be obtained in only 25 days retention. With a minimum depth of three feet the normal design flow resulted in a load factor of 400 population/acre. Considering the BOD load, it was 45 lbs/acre/day or 15 lbs/acre-ft/day. Caldwell recommended the use of two or more ponds. Operationally, Caldwell observed that the effluents from oxidation ponds were very green with lots of algae. The conventional sewage tests for BOD and suspended solids were found to be of little value in plant evaluation since they were rather high. There was a definite difference in the raw waste characteristics and the final effluent characteristics. While both contained BOD and suspended solids, the effluent did not create obnoxious conditions on standing as did the raw wastes. This fact made Caldwell question the value of these parameters in evaluating oxidation pond operations. He indicated that there was little of the original sewage in the treated effluent, only suspended algae. Caldwell was one of the first to recognize that the quantity of organic matter discharged in the effluent as algae cells could exceed the quantity of organic matter entering the pond in the raw wastes.

This simple observation is of extreme importance in understanding oxidation pond operations, especially in view of increasing stream quality regulations. It was observed that coliform bacteria were quickly destroyed in the presence of algae but the mechanism of destruction was not known. When periodic odors did arise, Caldwell recommended use of nitrates. While Caldwell supplied the best operational information to date, there was definitely a need for more information from field operations.

In 1956 Towne et al (10) presented a report on cooperative studies that the USPHS had undertaken with the state health departments. Their studies were divided into three areas: 1. basic data collection, 2. field studies, and 3. controlled experimental studies. The basic data collection was designed to gather all of the information available about existing ponds. Approximately 350 were in operation in the Southwest and the Midwest when this study was started. The field studies included the examination in depth of 5 oxidation ponds in North and South Dakota and of 34 ponds in Texas and Oklahoma. The controlled experimental studies were designed to produce fundamental data on the process mechanism. The primary field results were summarized in this report. The North and South Dakota ponds were from 4 to 27 acres with depths from 1.2 to 5.4 ft. The BOD loadings ranged from 7 to 17 pounds/acre/day. Four of the ponds were single cell ponds while the fifth pond had five cells. It was found that coliform bacteria reductions reached 99% more than 50% of the time. BOD reductions unfiltered samples were from 43% to 98%. In the winter the suspended solids were reduced by 80 to 84% but in the summer there were priodic increases to as much as 258%. Sulfides were generally present under ice cover but were absent in the summer. These latter two items reflected upon the action or lack of action of the algae. Scenedesmus was the predominant algae in the winter; while Euglena was dominant in the warm weather. Light penetration was reduced by ice cover to 0.5% to 15% of that reaching the surface. In the summer 99% of the light was absorbed in the upper 24 inches of the pond. Diurnal variations in photosynthesis caused the dissolved oxygen to vary from 4 to 6 mg/l at night to 38 mg/l in the late afternoon. The Texas and Oklahoma plants treated primary or secondary effluents in contrast to the raw sewage ponds in North and South Dakota. Only two ponds studied in Texas and Oklahoma treated raw sewage. The ponds averaged 3 ft depth and varied considerably in size, shape, and loading. The BOD loadings ranged from 12 to 225 lbs/acre/day. Operations were quite good with little impact from temperature variations such as were observed in the Dakotas. Thus, efforts were underway to develop the information needed for proper evaluation of oxidation ponds.

These efforts culminated in a symposium on waste stabilization lagoons in Kansas City, Missouri, in August, 1960.

While studies were underway in the United States, Wennstrom (6) presented extensive operational data on oxidation pond systems in Sweden. This plant employed four ponds in series after primary sedimentation. With a retention period of under 17 days, Wennstrom observed a BOD reduction from 159 mg/l to 20 mg/l. One innovation in these ponds was recirculation of the pond contents to produce better mixing and equalization of the material in the ponds. Extensive biological studies were carried out in this system of ponds yielding the most extensive zooplankton studies on oxidation ponds. Wennstrom clearly demonstrated the value of oxidation ponds in treating domestic sewage and the results to be expected in each pond operating in series, one with the other. Unfortunately, Wennstrom's study had limited circulation in the United States and went unnoticed for the most part.

In Australia Parker et al (12) utilized anaerobic ponds ahead of oxidation ponds for the treatment of wastewaters. The anaerobic lagoons were capable of removing 80% of the BOD with 5 days retention at 64°F. BOD loadings recommended were 600 lbs BOD/acre/day without any problems. They found that algae in the effluent greatly influenced the final BOD and suspended solids. The oxidation pond removed all of the sewage contaminants so that the algae were the cause of both the BOD and the suspended solids in the effluent. The final BOD ranged from 20 to 50 mg/l. Parker questioned the desirability of discharging the algae in the effluent even though Caldwell (1) had indicated it was not a problem.

Neel and Hopkins (9) reported on extensive tests carried out at Kearney, Nebraska, from May, 1954 to July, 1955. The value of this study was limited by the fact that the Kearney oxidation pond was constructed in very porous soil and tended to leak excessively. Approximately 75% of the wastes added to the oxidation pond were lost by evaporation and percolation. The Kearney oxidation pond had a surface area of 10 acres and was designed as an experimental unit for determining the feasibility of using oxidation ponds for treating all of the sewage from Kearney. This latter fact accounted for the large amount of data collected. Examination of the data indicated that the pond temperature ranged from 1 C to 34 C. The turbidity in the oxidation pond was created by algae and varied with the seasons of the year, reaching a maximum in the summer. These algae showed very little tendency to settle. Odors were unnoticeable as long as there was adequate oxygen in the pond. When anaerobic conditions developed during the winter, odors were quite offensive. Ice cover on the lagoon acted as a lid and kept the odors within the pond until the spring thaw. Floating solids created definite operational problems and odors. Wind action was responsible for mixing in the pond. The wind action was sufficient to cause a definite difference in elevations in the pond and to induce a strong backflow along the bottom of the pond. Currents of 0.3 to 0.7 fps were measured along the shore. In spite of the wind action, normal waves were not formed. It was believed that synthetic detergents prevented proper wave formation. One thing for certain, the observation reported by Caldwell (1) that surface characteristics could be used to determine treatment efficiency was confirmed in this study. When the organic wastes are stabilized in the pond, a light wind will create definite waves which are visible on the surface. When organic matter remains untreated, the surface of the pond is glassy smooth even with a light breeze. The dissolved oxygen concentration in the pond ranged from 0 mg/l to 36 mg/l. Wind action was responsible for mixing so that the dissolved oxygen or lack of dissolved oxygen occurred at all depths. The average BOD in the sewage was 149 mg/l. The effluent BOD ranged from 18 mg/l to 94 mg/l. Neel and Hopkins were also faced with the fact that oxidation pond effluent BOD values did not represent the stabilization of the domestic sewage; but reflected the growth of algae. Examination of other data indicates the difficulties that arise in evaluating oxidation ponds operations on a simple influent-effluent relationship. The influent can show considerable daily variation in waste characteristics while the pond effluent is unaffected by these variations. This is most clearly shown in the chloride data where some data indicated more chlorides entering the pond than leaving. The pond operated as a large surge basin for leveling out waste variations. Real data evaluation for oxidation ponds requires extensive data collection to determine average influent and effluent values.

With loss of pond water by percolation, tests were run on the chemical quality of water in nearby wells. Chlorides and synthetic detergent analyses definitely showed that the ground water was being contaminated by the seepage from the oxidation pond. The reduction of coliform bacteria averaged 83%. The predominant algae were Chlamydomonas, Microactinium, and Euglena. Algal growth and dissolved oxygen concentrations in the oxidation pond were correlated generally with the available light. Ciliated protozoa and rotifers were the primary forms of zooplankton observed in the pond. The loss of the pond contents by percolation and contamination of the ground water forced cessation of the Kearney study and prompted the search for another site for evaluating oxidation ponds.

The next test site for the USPHS was at Fayette, Missouri (4,13). A 15 acre oxidation pond system was constructed with five one acre test ponds and one 10 acre pond. This system was tested for 13 months in 1957-58 in one series and then changed for a second 10 month series in 1958-59. In the 1957-58 tests all units operated with 2.5 ft water depth except the large unit which had 3.0 ft water depth. The load on each cell was adjusted to a BOD/acre/day basis as follows: 20, 40, 60, 80, and 100 lbs BOD/acre/day. The large cell had a 15 lbs BOD/acre/day load. The average data for the first series of test is given in Table 1.

Table 1

Fayette, Mo., Oxidation Pond Operational Data, 1957-58

Unit	Total Alkalinity (mg/l)	Oxygen (mg/l)	BOD (mg/l)	Total PO_4 (mg/l)	Total N (mg/l)	Coliforms (MPN/ 100 ml)
Raw Sewage	255	-	267	42.7	160.6	40×10^6
1. 20 lb/A/dy	174	16	34	8.2	11.4	13×10^3
2. 40 lb/A/dy	178	15	38	9.7	13.8	20×10^3
3. 60 lb/A/dy	187	14	48	13.8	18.4	28×10^3
4. 80 lb/A/dy	199	11	49	12.8	17.4	34×10^3
5. 100 lb/A/dy	191	11	47	12.8	17.1	64×10^3
6. 15 lb/A/dy	175	13	30	8.7	11.6	15×10^3

These data reflect sufficient data to permit reasonable conclusions to be drawn. The impact of increasing the organic load and reducing the hydraulic retention time is shown in these results. The 100 lbs BOD/acre/day loading rate produced a 17 day retention period which was one-fifth that in the 20 lbs BOD/acre/day unit. Of all of the data the coliform count reflected the effect of the detention period. Essentially, the effluent coliform count was a function of retention period in the pond, reflecting a linear die away relationship. Effluent quality was essentially related to the algal growth with load and retention period having only a slight effect on algal growth. Maximum reduction in alkalinity and maximum oxygen production occurred in the long retention period system. As the retention period decreased, the alkalinity rose and the oxygen produced fell. The effluent BOD increased as did total phosphate and total nitrogen. The 160 mg/l of total nitrogen is abnormal for domestic sewage and was essentially organic nitrogen that was in the form of suspended solids which could be easily removed by sedimentation in the ponds. It was concluded from the first phase that 40 lbs BOD/acre/day was probably the best load for this area of the country because of winter operations and ice cover. Two cells were considered better than one cell so that one cell could be operated in the summer and both cells could be operated in the winter. Winter operations with ice cover confirmed the 20 lbs BOD/acre/day as maximum loading to keep anaerobic conditions from developing. A two cell system operating at an average of 40 lbs BOD/acre/day could have a 60 lb BOD/acre/day load on the first cell and a 20 lb BOD/acre/day load on the second cell. Where ice cover is not a problem, design can be based on 3 langleys/lb BOD during the minimum light month.

In the second series the plant operation was changed with cell 1 being loaded at 120 lbs BOD/acre/day. Cell 3 was loaded at 100 lbs/acre/day with cell 2 taking the effluent from cell 3 for series operation. Cell 4 was loaded at 60 lbs BOD/acre/day with an increase in water depth to 5 ft. Cell 5 was also loaded at 60 lbs BOD/acre/day with the depth remaining at 2.5 ft. The loading on cell 6 was only 8 lbs BOD/acre/day. The average sewage flow over the 10 month operating period was 216,000 gpd, the same as in the first period. The operational data are shown in Table 2.

Table 2
Fayette, Mo. Oxidation Pond Operational Data, 1958-59

Unit	Total Alkalinity (mg/l)	Oxygen (mg/l)	BOD (mg/l)	Total PO_4 (mg/l)	Total N (mg/l)	Coliforms (MPN/100 ml)
Raw Sewage	281	-	268	44	152	$150x10^6$
1. 120 lb/A/dy	192	8.2	53	10.8	12.9	$31x10^3$
2. 100 lb/A/dy	187	7.7	50	8.0	10.8	$33x10^3$
3. ---	172	10.6	26	3.2	4.8	$6x10^3$
4. 60 lb/A/dy	184	7.2	40	6.9	9.6	$22x10^3$
5. 60 lb/A/dy	184	8.8	44	6.6	9.9	$17x10^3$
6. 8 lb/A/dy	155	9.6	30	4.6	6.7	$7x10^3$

These data followed similar trends as before with higher loadings reflecting poorer effluent quality. The importance of series operation was clearly demonstrated with cells 2 and 3. In effect all of the waste stabilization had occurred in cell 3 with cell 2 merely permitting algae to grow and die. The algae growth increased the dissolved oxygen while decreasing the alkalinity, the phosphate and the nitrogen. the lower BOD in the effluent reflects the fact that some of the algae settled out in the pond and were not lost in the effluent. Further algae separation would have produced even better effluent quality. The two cells loaded at the same rate but with different water depths produced almost identical results. The shallower cell produced more oxygen and more algae and gave a higher BOD in the effluent. Detailed evaluation of these two units showed that stratification definitely occured in both units. Stratification was most apparent in the 5 ft cell. The lower layer was anaerobic while the upper layer was aerobic. This fact reinforced the importance of mixing to produce good oxygen distribution. The small one acre cell made mixing difficult and produced conditions that would not occur on large oxidation ponds. Care must be employed in translating the results of these small cells to large plants. The hydraulic differences that are produced are significant. Samples taken of the bottom by coring indicated that the oxidation pond accumulated solids at the rate of one foot every 25 years so that solids accumulation is not an important consideration in oxidation ponds except over very long time periods.

The next major study was made by the USPHS at Lebanon, Ohio (14). Two ponds, one 0.32 acres and the other 0.27 acres, were studied as to the fate of pathogenic bacteria at high loading rates. Pond I was loaded from 49 to 82 lbs BOD/acre/day and Pond III was loaded at 117 to 194 lbs BOD/acre/day. The retention time in Pond I was 45 days while the retention time in Pond III was 15 days. Concentrated testing was carried out for a period of 10 consecutive days during each of the four seasons of the year. The total coliforms in the raw sewage were normally around 3.3×10^6/100 ml. Pond I effluent contained around 300×10^3/100 ml and Pond III effluent contained around 600×10^3/100 ml. Fecal coliforms were around 0.9×10^6 in the raw sewage and around 60×10^3 in Pond I and 170×10^3 in Pond III. The fecal streptococci were 3.1×10^6 in the raw sewage and around 52×10^3 in Pond I and 200×10^3 in Pond III. The raw sewage BOD was 276 mg/l with an effluent of 57 mg/l in Pond I and 97 mg/l in Pond III. A special study of photosynthesis showed the relationship between oxygen demand and oxygen production. On one day there was an oxygen deficit while on the other day there was an excess of oxygen. It is important that oxygen resources balance the oxygen demand. It was demonstrated that the effluent could be treated with 10 mg/l chlorine and 15 minutes contact to achieve reasonable coliform reductions.

A shallow lagoon system, operating depths of 0 to 1.87 ft., was studied by Nemerow and Bryson (15) at Hancock Air Force Base near Syracuse, New York. The primary cell of 1.7 acres, loaded at 130 lbs BOD/acre/day, showed 69 percent removal of BOD and the secondary cell of 6.5 acres, loaded at 10.9 lbs BOD/acre/day, showed 88 percent removal of BOD. This lagoon also reduced phosphates to 3 to 4 mg/l. Much of the liquid in the cells was lost to percolation and evaporation, approximately 30 percent of total, so that during seven of the twelve operating months no discharge was realized. This study relates the difficulties in attempting to operate lagoons of shallow depths, apparently due to lack of compaction or sealing of the constructed cells. Growth of excess vegetation in and around the lagoon resulted with cat tails, marsh grass, small trees and weeds being evident in the cells. Mosquitoes were prevalent during the summer months and rats and muskrats caused extensive damage to the banks and dikes. Since operation of the lagoon resulted in sludge build-up, and since operating depths were shallow, it is expected that methane fermentation did not occur as one would expect in deeper ponds where anaerobiasis would be expected at the mud phase. Although the authors of this study did not indicate presence of gas formation in the lagoon, and since sludge build-up was a problem, it is assumed that methanogenic organisms were not present in large numbers.

Middlebrooks *et al* (16) examined the problem of solids accumulation in oxidation ponds. Core samples were collected from 15 oxidation ponds in Mississippi loaded at around 25 lbs BOD /acre/day. Solids were found to accumulate around the oxidation pond inlet. Mathematical evaluation of the data on the IBM 1620 computer led to an equation that predicted the rate of sludge accumulation at one foot every 27.6 years. This agreed closely with the data of Clare *et al* (13).

In 1967 Williford and Middlebrooks (17) studied two experimental oxidation ponds at Mississippi State University. The first oxidation pond had 0.74 acres of surface area with a 5 ft water depth while the second oxidation pond had a surface of 68 acres with a 3 ft water depth. The study covered a 14 month period. The raw sewage had a BOD of 188 mg/l. Both oxidation ponds were loaded at 100 lbs BOD/acre/day. The effluent from the 5 ft pond had 45 mg/l BOD while the effluent from the 3 ft pond had 55 mg/l BOD. These data are very close to those obtained at Fayette, Missouri (4,13). As expected, the pH was the highest in the summer during daylight hours. Maximum pH recorded in August was 10.8. Normal variations showed a range from 8.3 just before dawn to 9.9 in the late afternoon. The carbon dioxide concentration in the pond was a maximum at night and a minimum in the day, reflecting endogenous respiration of the algae in the dark and their metabolism of carbon dioxide in the daylight. The 3 ft pond averaged 6.1 mg/l DO at thessurface and 1.8 mg/l at the bottom. The 5 ft pond had 5.8 mg/l DO at the surface and 0.95 mg/l at the bottom. During the summer the ponds were devoid of oxygen at the bottom. Mixing again is the key to oxygen distribution.

Although California was a leader in developing the oxidation pond, it was slow to utilize the raw sewage oxidation pond. In order to develop a better understanding of the operation of these systems a study (18) was made of 20 oxidation ponds within the state of California. Odors were noticeable at six of the ponds while complaints have been received at five ponds. Sodium nitrate was the only material used to reduce odor nuisances. Most of the oxidation ponds were located downwind from the community they served and 3/4 of the plants had clear windsweeps. Based on results of the initial visitations five oxidation ponds were selected for detailed study. Of necessity the tests were short term, one week in the winter and one week in the summer. The Woodland oxidation pond system consisted of 12 two acre oxidation ponds with only five units in operation, all in parallel. The Esparto oxidation pond system has 5 two acre ponds. Two ponds act as primary units in parallel with their effluent being discharged to the final three ponds which all operate in series. The last pond is actually a percolation pond. The Shastina Sanitary District oxidation pond consists of four ponds in series. The Los Banos oxidation pond system consists of two ponds in series. Each pond has an area of 85 acres. The Orland oxidation pond system has two 10 acre oxidation ponds and two 15 acre ponds. The 10 acre ponds operate in parallel as primary oxidation ponds with the effluent discharging to the 15 acre ponds. Olive brine wastes presented a special problem in this pond. The BOD data are given in Table 3.

Table 3

BOD Data Collected at Five California Oxidation Ponds

Pond	BOD Load (lbs/acre/day)	BOD Influent (mg/l)	BOD Effluent (mg/l)
Woodland			
Winter	29	125	42
Summer	25	67	26
Esparto			
Winter	16	119	11
Summer	15	165	25
Shastina Sanitary District			
Winter	50	85	19
Summer	161	135	2
Los Banos			
Winter	77	295	38
Summer	78	265	26
Orland			
Winter	17	145	20

These data showed a wide variety of results with little correlation between effluent quality and BOD loading. The most important aspect was the use of series ponds. There was no doubt that multiple ponds produced better effluent quality than the single cell pond. The removal of algae was the important difference.

Although experience with oxidation ponds in sufficient depth to be meaningful is limited, the data have tended to follow the same trends. There is enough data that it is possible to state certain definite design and operating principles. Proper application of these principles should produce better oxidation ponds for domestic sewage. Since industrial wastes merely contain a different form of organic matter than domestic sewage, the same principles should be derived by examining operating data from industrail waste oxidation ponds.

Industrial Wastes

In 1963 Porges (18) reported that 827 ponds were being used by industry in the United States in 1962. Of these 827 ponds the canning industry had 29% and the meat and poultry industry had 20%. There were 239 oxidation ponds of which 142 were single cell ponds and 77 were series ponds. There was not much experimental data to permit complete evaluation of the oxidation ponds but some data were presented. Table 4 shows the median values of the BOD loading and removal as well as depth and retention period.

Table 4

Median Values for Industrial Oxidation Ponds

Industry	BOD Loading (lbs/acre/day)	%BOD Reduction	Retention Time (days)	Depth (feet)
Canning	139	98	38	5.8
Meat & Poultry	72	80	70	3.0
Petroleum	28	76	25	5.0
Dairy	22	95	98	5.0
Paper	105	80	30	5.0
Rendering	36	76	48	4.2

Industrial oxidation ponds have been loaded greater than conventional domestic sewage oxidation ponds in an effort to keep the land requirements low. The net result has been a tendency to overload industrial ponds more than domestic sewage ponds.

The data are quite normal except for canning wastes. It is highly improbable that canning ponds produce 98% BOD reduction. Of the 38 oxidation ponds reporting serious odor problems, 16 were canning ponds. Odor nuisances occur only when the oxidation pond is overloaded and is not producing satisfactory treatment. The other data seem normal considering the waste characteristics. The majority of industrial waste systems have wastes with a high BOD concentration. Without satisfactory mixing for distribution of wastes, the concentrated organics create anaerobic pockets and produce unsatisfactory results. A few industrial wastes have high suspended solids that are quickly removed by sedimentation in oxidation ponds.

The canning industry waste disposal situation was recently reviewed by Canham (19). He indicated that oxidation ponds were used primarily as holding ponds. The short canning season results in the production of wastes over a few months period. The oxidation ponds are sized to hold the entire production of one seasons canning. Because of odor production sodium nitrate has been used extensively by the canning industry to act as a supplemental source of oxygen for the bacteria stabilizing the wastes. The soluble sugars in canning wastes permit rapid bacteria metabolism and create adverse environmental conditions. Recent use of spray irrigation has been tried in a number of instances as have experiments with aerated lagoons. Few if any canning ponds have been loaded at BOD rates acceptable for oxidation pond operations. The high concentration of BOD does not permit distribution of the load properly thoughout the needed liquid volume for good operation.

The meat packing industry has made extensive use of oxidation ponds. The high suspended solids and high BOD of packinghouse wastes makes them suitable for anaerobic lagoon treatment ahead of oxidation ponds. Thus it is that the oxidation pond has assumed primarily a role as a secondary treatment unit. Steffen (20) reported that loadings ranged from 50 lbs BOD/acre/day in South Dakota to 214 lbs/acre/day in Delaware. With the first anaerobic-aerobic system constructed in Moultrie, Georgia, in 1955, the meatpacking industry was embarked on the concept of anaerobic lagoons followed by oxidation ponds. The data presented by Sollo (21) for 1959 indicated a raw waste BOD of 1060 mg/l. The effluent from the anaerobic lagoon was 163 mg/l, 85% reduction. The effluent from the oxidation pond averaged 58 mg/l. The total treatment plant BOD reduction was 94% while the BOD reduction within the single cell oxidation pond was 64%. These results are typical of the data reported for other meat packing plants.

Cooper et al.(22) investigated the treatment of organic industrial wastes in California by ponding. A rendering plant waste was discharged to an anaerobic lagoon with an average load of 228 lbs BOD/acre/day for a retention period of 160 days. The raw wastes had a BOD of 1870 mg/l. Approximately, 88 percent BOD reduction was obtained in the aerobic pond. The oxidation pond following the anaerobic pond was loaded at 15 lbs/acre/day. The BOD reduction in the oxidation pond averaged 78 percent while the overall plant reduction approached 98 percent. A petroleum refinery had 144 acres of oxidation ponds with a 4-5 ft depth and a waste flow varying from 4 to 20 MGD. The average BOD loading was 54 lbs/acre/day with an influent BOD of 77 mg/l. The effluent BOD averaged 45 mg/l for only 38% reduction. Examination of the phenol reduction indicated 88.5%. This difference in BOD reduction and phenol reduction clearly shows the impact of the algae in the effluent. It would appear that this refinery pond had an algal population quite similar to that of domestic sewage. Even with industrial wastes the effluent BOD is determined by the algae when loading rates are employed with weak wastes.

Nemerow (23) showed 92% BOD reduction in a two stage pond system receiving poultry wastes. The first pond was loaded at 935 lbs BOD/acre/day with a 7.4 day retention period. This second pond was operated as an oxidation pond at 79 lbs BOD/acre/day with a 2 ft depth. With the algae in the effluent the BOD reduction was only 9.2%; but with removal of the algae the BOD reduction was 70%. Once again the importance of algae in the effluent quality was clearly demonstrated.

Oxidation ponds have been used for canning and poultry processing wastes by the Campbell Soup Company (24). A plant in Listowel, Canada, has 69 acres of oxidation ponds in two cells. The BOD loading was 67 lbs/acre/day. The first cell had a BOD of 41 mg/l in the effluent. Filtering out the algae dropped the BOD to 4 mg/l. The second cell dropped the BOD to 35 mg/l with 7.9 mg/l remaining after the algae were filtered out. Once again the oxidation pond with wastes similar to domestic sewage reacted the same. Industrial wastes in themselves pose no special problems or represent any unusual set of conditons that require a different set of design and operational criteria. At Tecumseh, Nebraska, a 3 pond system of 15 acres each was originally designed for 50 lbs BOD/acre/day; but actual operational data indicated a loading in excess of 100 lbs BOD/acre/day. In an effort to reduce the load prior to the oxidation ponds, an anaerobic lagoon was constructed with a 15 ft depth and was loaded at 12 lbs BOD/1000 cf/day. The raw waste BOD averaged 900 mg/l. The anaerobic lagoon had an effluent with 310 mg/l BOD; while the oxidation pond effluent averaged 90 mg/l.

The addition of whey wastes to a domestic sewage oxidation pond system in El Centro, California, was reported (25) to have created serious operational problems. The readily degradable organics in the whey produced an excessive amount of organics in the oxidation ponds. The El Centro treatment system consisted of primary sedimentation with three parallel oxidation ponds covering 50 acres. With a settled BOD of 210 mg/l the BOD loading on the oxidation ponds ranged from 50 to 70 lbs/acre/day. The whey wastes stimulated sulfate reducing bacteria with the production of hydrogen sulfide. The hydrogen sulfide was partially lost into the atmosphere with the creation of odor nuisances and was partially precipitated by the iron in the sewage. The addition of nitrates helped to control the odor nuisances but considerable quantities of nitrates were needed to supply the oxygen demanded by the microbes metabolising the whey wastes. A dilution of whey of 1:360 was required if the oxidation ponds were to operate satisfactorily.

Extended collection of data by industries on oxidation pond treatment has been rather limited. Few industries have been willing to present their data to the public since the effluents were usually not as good as they had hoped. The strong BOD concentration of most industrial wastes and the high solubility of some industrial wastes requires some basic modifications in the design and operation of oxidation ponds over that used for conventional domestic sewage. In spite of these differences the operational data from properly designed and operated oxidation ponds treating a variety of industrial wastes are identical to the results obtained from domestic sewage systems.

WATER QUALITY CRITERIA

The purpose of any wastewater treatment process is the production of an effluent which can be discharged back into the environment without creating further pollution. In reccent years concern over water pollution has increased. The net effect of this concern for water pollution has been the establishment of stringent water quality criteria. The 1965 Water Quality Act required each State in the United States to establish satisfactory water quality criteria that met with Federal approval. In effect, a national set of water quality criteria were being requested with the forced cooperation of each State. The Water Quality Act permitted the Federal government to establish criteria if it disagreed with the criteria adopted by the States. Currently, efforts are underway to establish national effluent standards without regard to the receiving stream. There are definite advantages to effluent standards and there is every reason to believe that national effluent standards will be adopted within the next few years. Thus, when one honestly looks at the use of oxidation ponds for wastewater treatment systems, one must examine the effluent quality very carefully.

Recently, Middleton and Bunch, (26) raised the question as to whether or not oxidation ponds were going to find continued use for wastewater treatment. They recognized that oxidation ponds had grown in popularity during the decade of the sixties; but they were concerned if the effluent quality being produced by oxidation ponds was adequate for future conditions. Currently, high quality treated wastes were expected to have BOD values under 30 mg/l, COD values under 75 mg/l, and suspended solids values under 25 mg/l at least 90 percent of the time with 24 hr composite samples. The fecal coliforms were expected to be under 200/100 ml samples. In effect, Middleton and Bunch were suggesting an effluent standard for oxidation ponds. Examination of existing oxidation ponds indicated a higher BOD than that suggested. Algae seemed to be responsible for both the high BOD and the high suspended solids in the effluent. The spectre of ultimate BOD in contrast to BOD_5 was raised briefly. They felt that there were no known methods for easily removing the algae from the effluents. It was also indicated in their report that the current effluents probably could not meet the desired fecal coliform level. While they did not condemn the oxidation pond as a method for treating wastewaters, Middleton and Bunch definitely expressed serious doubts as to its continued use in the future.

Reservations as to the future of oxidation ponds has been expressed more emphatically by Barsom and Ryckman (27). They felt that oxidation ponds have created a number of problems, such as odors, a highly colored effluent, high suspended solids effluent, mosquito and insect problems, and noxious weeds. In order to examine oxidation ponds Barsom and Ryckman developed an arbitrary failure scale based on BOD and suspended solids in the effluent. They felt that first degree failure occurred when the effluent BOD exceeded 20 mg/l and the suspened solids exceeded 25 mg/l. A second degree failure occurred at BOD values above 30 mg/l and suspended solids values above 35 mg/l. The third degree failure occurred when the BOD exceeded 40 mg/l and the suspended solids exceeded 45 mg/l. Examination of published data on oxidation pond operations indicated that of 20 ponds studied, 16 ponds exceeded third degree failures for BOD and the remaining 5 ponds exceeded second degree failures. With regard to suspended solids data 15 plants were studied and all showed third degree failures. It was not surprising to note that Barsom and Ryckman concluded that "continued use of oxidation ponds as presently designed and operated will not enhance, restore, or maintain the quality of the receiving stream."

There was no doubt in their minds that oxidation ponds had no place in the future of wastewater treatment.

There is no doubt that a review of the operational data already presented earlier together with the review by Fitzgerald and Rohlich (28) confirms the fact that oxidation ponds have not produced a high quality effluent consistently. The quality of the oxidation pond effluent is primarily dependent upon the algae discharged. The algae make up the suspended solids and create the major fraction of the carbonaceous BOD. It has been shown many times over that if the algae are removed, a very high quality effluent can be produced. The problem is how to remove the dispersed algae. A number of methods have been proposed for removing the algae but none have proven satisfactory to date. Microscreening, sand filtration, and chemical precipitation have proven too complex and too expensive for routine use.

Early investigations indicated that algae did not create problems in the receiving waters and that it was not fair to use the dark bottle BOD test as a measure of the impact of the algae on the stream. Unfortunately, there is no easy way to evaluate the impact of the oxidation pond effluents except to examine the receiving streams. Few investigators have made downstream evaluations of oxidation pond discharges. Two recent studies have been made which contribute significant information to this problem. King et al (29) carried out a study on Bear Creek in Columbia, Missouri, where two oxidation ponds discharge their effluents. The stream flow averaged 0.88 cfs below the oxidation ponds with the ponds making up 25% of the flow. They found that the algae in the lagoon effluent had a detrimental effect on the receiving stream. The oxygen generated by algae in the stream can be used by the other organisms but it cannot be considered as free oxygen and must be paid off when the algae settle to the bottom of the stream and undergo respiration. They felt that the stream must be considered as part of the treatment system with atmospheric reaeration satisfying the ultimate oxygen demand. Long term BOD tests revealed that the effluent BOD was only 20% of the ultimate BOD. The ultimate BOD was 90 to 95% of the effluent COD. It appeared that nitrification played an important part in the long term BOD data.

Bain et al (30) studied the impact of the effluent from oxidation ponds at Stockton, California on the estuary of the San Joaquin River. Their data showed that the algae from the oxidation pond settled in the estuary and demanded more oxygen than was produced. The zooplankton population showed a definite increase below the oxidation pond discharge over the area above the discharge. They too, found that 5 day BOD was approximately 20% of the ultimate BOD.

Thus, it was shown that the algae have to be considered in evaluating stream quality. Once again, nitrification posed a serious problem in the receiving stream the same as the algae. Part of the nitrification problem was related to the algae but part of it was related to the excess nitrogen in the treated sewage.

The data obtained from these two field studies together with the multitude of data on the effluent characteristics from oxidation ponds clearly points to the fact that the discharge of algae clearly poses a problem in meeting current water quality criteria. Filtered BOD data showed that removal of the algae resulted in an effluent that could meet current water quality criteria with regards to BOD. The solution to the water quality dilemma of excessive BOD in the oxidation pond effluent would be simply to remove the algae prior to final discharge of the effluent into the receiving stream.

A number of investigators have tackled the problem of algae removal. Oswald *et al* (31,32) found that centrifugation or chemical flocculation were the most effective methods for removing the algae from the oxidation pond effluent. In high rate oxidation ponds, designed primarily for rapid algae growth, the BOD was reduced from 121 mg/l to 2.1 mg/l with only 3 days retention when the algae were removed by chemical flocculation. Van Duuren and Van Duuren (33) developed a complex system for algae removal from a maturation pond effluent in South West Africa. They used primary sedimentation with alum followed by lime and chlorine, a second sedimentation tank, a sand filter, a carbon filter and final chlorination. The results were excellent at 125-170 mg/l alum with 25 to 40 mg/l suspended solids. Further studies by McGary (34) showed that alum and cationic polyelectrolytes could be used to remove algae from high rate oxidation ponds. Golueke and Oswald (35) reported on the use of cationic resins for removing algae. The algae were removed by the resin and could be regenerated by backwashing with water. The algae tended to aggregate around the resin beads and remained aggregated in the backwashing process. The chemical regeneration of the resins made this process too expensive. A simple concept that was proposed by Martin (36) has been successfully tried on oxidation pond effluent in the laboratory. A shallow rock filter operating on an upflow basis removed 80 to 90% of the algae when operated at the rate of 12.5 gal/sf/day. It appeared that 20 cf of rock would be required for each per capita design basis. The simplicity of the rock filter and the laboratory data to date makes further testing in the field most desirable. If the rock filter could effect at least 50 percent reduction in algae, most effluents would be able to meet current water quality criteria as well as the arbitrary standards of Barsom and Ryckman (27). Removal of algae is definitely a high priority research item in view of the widespread use of oxidation ponds at the present time. Removal of the algae would not only produce a satisfactory BOD quality but it would also produce a satisfactory suspended solids quality.

The survival of pathogenic microorganisms has always been a major concern in sewage treatment. One of the objectives of wastewater treatment is the reduction of harmful microorganisms. While direct isolation and study of pathogenic microorganisms is most difficult, treatment plant evaluation is generally based on the reduction in coliform bacteria. Neel et al (4) found that the coliform survival was related to fluid retention time in the oxidation ponds. While 99.99 percent coliform reduction was possible in their ponds, the effluent still had an average of 14.7 x 10^3/100 ml. This linear rate relationship for the survival of coliforms was noted by Meron et al (8). They calculated that an 80 day retention period was necessary to produce an MPN of 2.

Fitzgerald and Rohlich (28) felt that oxidation ponds could reduce fecal coliforms down below 100/ml, an MPN of 10,000. An extensive study by Parker (37) in Australia utilized 8 ponds in series. The fecal coliform bacteria decreased from an MPN of 6 x 10^7/100 ml to 13 during the summer with 38.5 days retention. Enumeration of S. faecalis showed a drop from 1 x 10^5/ml to 0.09/ml. In the winter only 6 ponds were in use. The fecal coliforms decreased from a MPN of 5.4 x 10^7/100 ml to 4.4 x 10^4 in 30.5 days retention. The S. faecalis count dropped from 4.8 x 10^4/ml to 43/ml. The bacteria reductions were related to retention and temperature as would be expected from fundamentals.

Cody and Tischer (38) attempted to isolate Salmonella and Shigella from oxidation ponds. While they were able to isolate Salmonella occassionally; they were unable to isolate any Shigella. The Salmonella were found in samples collected near the waste influent to the pond and were not found in the effluent from the oxidation pond. They concluded that the coliform reductions through oxidation ponds gave a good indicator of the reduction of enteric pathogenic bacteria. It was concluded that oxidation ponds should not pose a hazard from bacterial pathogens. Hok (39) and Hsu and Kruse (40) reported that Salmonella abortus equi did not survive long when added to an oxidation pond. It was recovered on the third day but was lost on the fourth day. The environment in the oxidation pond is definitely not suited for the survival of pathogenic bacteria.

Slanetz et al (41) studied three oxidation ponds treating domestic sewage for reductions in coliforms, Salmonella, and enteric viruses. They found that three ponds in series gave 95 to 99 percent reduction in coliforms and fecal streptococci. Most samples examined for Salmonella were negative while many of the virus samples were positive. Survival of enteric microorganisms were greater in the winter than in the summer, reinforcing the temperature factor. Little et al (42) examined 9 oxidation ponds in the Southeastern part of the United States for fecal coliforms. There was no correlation between fecal coliforms and BOD loading on the oxidation ponds; although there appeared to be a correlation between fecal coliforms and retention time. The longer the fluid retention time in the oxidation pond, the lower the number of fecal coliforms surviving were observed. The use of multicell ponds gave better results than single cell ponds as a result of less short circuiting and better retention of the wastes flowing through the ponds. They believed that effluent chlorination could be used effectively in single cell ponds to reduce the coliform population.

Hom (43) examined the chlorination of an oxidation pond effluent treating domestic sewage from Concord, California. He found that with 5 mg/l chlorine he was able to obtain 99.99 percent reduction in coliforms with 30 minutes contact time. Increasing the chlorine concentration resulted in better coliform reductons; but the algae were also killed and lysed, increasing the BOD of the chlorinated effluent. Thus, it was necessary to chlorinate carefully to kill the coliforms without damaging too many algae. The effluent quality from the Concord oxidation pond was better than most effluent, a BOD under 20 mg/l and suspended solids of 30 mg/l. The effluent coliform concentration was 2.2×10^5/100 ml, considerably higher than most of the previous data reported. Since information concerning the oxidation pond design and operation were not included, it was difficult to evaluate the applicability of these results to other situations.

Chlorination of oxidation pond effluents poses a number of problems. First, the high concentrationof algae tend to react with the chlorine in much the same way that bacteria do. Death of the algae would result in the release of organics and create a definite BOD. The immediate impact of the dead algae on the receiving stream would be greater than if the algae were alive. Second, the chlorine reacts readily with ammonia and other chemical compounds to form chlorinated compounds. Chloramines are not as effective bactericidal agents as chlorine. The addition of chlorine to organic compounds results in the formation of chlorinated hydrocarbons which can be toxic to biological life in the receiving stream. Often, the chlorinated hydrocarbons are toxic to the bacteria in the BOD bottle, giving the impression that the chlorine oxidized the organic matter when all that really happened was that the chlorine formed toxic chlorinated hydrocarbons. This fact explains why early research on sewage chlorination gave high values for BOD reductions for relatively low chlorine doses. Oxidation of organic matter requires a high chlorine dose. Virus, being pure organic material, require partial oxidation to produce irreversible reactons. Considerable study is needed before chlorination of oxidation pond effluents directly is recommended as standard practice.

One question that no one raised was the required effluent quality as compared to the desired effluent quality. If it were possible, a bacteria free and a virus free effluent would be desired. There could be no disease transmission if there were no microbes to transmit them. Since it is not possible to achieve the desired effluent quality, what should the required effluent quality be? Currently, there is no correlation between existing water quality criteria for fecal coliforms and enteric disease in the United States. One of the prime purposes of wastewater treatment is the protection of public health by prevention of the transmission of pathogenic microorganisms through water. There is a need to be safe in selecting water quality criteria but there is a limit on the practical degree of treatment needed to be safe. Currently, water quality criteria have been established arbitrarily without regard to disease transmission. In view of the economics of chlorination and the potential dangers from chlorinated hydrocarbons, it is essential that sound bacteriological water quality criteria be established. Further research in this vital area is definitely needed.

It has been well demonstrated that pathogenic microbes decrease with increasing retention time in ponds. Storage has long been considered as the simplest and most effective method for decontaminating water. Originally, oxidation ponds were designed with relatively long retention periods, 90 to 120 days, and multiple cells were recommended to maximize the flow through time. As experience showed that oxidation ponds could handle heavier organic loads than originally anticipated, the retention time decreased proportionately. The multiple ponds were shifted to single ponds since high quality effluents were not too critical in most oxidation pond installations. The net effect was that oxidation ponds shifted from being capable of producing high quality effluents without effort to producing marginal effluents without effort to producing marginal effluents. It appears that bacteriological quality suffered the most. Experience also indicates that marginal oxidation pond effluents can be shifted to high quality effluents with a minimum of effort and without loss of existing treatment investments.

As water quality criteria become more severe, oxidation ponds will have to meet new challenges. In some areas phosphate removal could pose a new condition. Nitrogen removal or total nitrification has also been suggested for some streams and lakes. It will be interesting to see how oxidation ponds meet the ever changing water quality criteria.

OXIDATION POND CONCEPTS

Oxidation ponds have, more often than not, been built on the basis of past experience with little regard to basic concepts of biological treatment. If oxidation ponds are to be designed and operated at their optimum level, it is essential that the design engineer understand the fundamental microbiology and biochemistry of the oxidation pond system. Without the microbes, there could be no chemical reactions to produce ultimate stabilization. Some of the microbes produce desirable chemical reactions and some of the microbes produce undesirable chemical reactions. In the past the engineer had no idea of which group of microbes would grow and to what extent. His experience was basically one of a continuous series of surprises that were never tied together into any meaningful fabric that could be used in future designs. The microbial reactions in oxidation ponds follow specific patterns and are entirely predictable and reproducible. Careful application of these microbial fundamentals can be used to design oxidation ponds that can meet any desired effluent criteria currently in effect or that might be adopted in the future.

Microorganisms

It was recognized very early that oxidation ponds operated on a bacteria-algae symbiosis in which the bacteria aerobically stabilized the organic matter while the algae grew autotrophically on the stable end products of bacteria metabolism and produced excess oxygen for the bacteria to use. The algae were the microroganisms that seemed to make the difference in the oxidation ponds. The most common algae reported in oxidation ponds include:

Euglena (44)(45)(4)(5)(8)(9)(10)(46)(37)
Chlamydomonas (45)(4)(5)(9)(46)
Chlorogonium (4)(46)
Microactinium (4)(9)(37)
Ankistrodesmus (4)
Scenedesmus (4)(5)(10)(46)(35)(37)
Chlorella (45)(4)(5)(8)(46)(35)(37)(43)(47)
Oscillatoria (4)(46)(47)
Anabaena (4)

Carteria (46)
Phormidium (46)
Navicula (37)
Closterium (37)
Anacystis (47)

The above list of algae is not intended as a complete list of algae that are found in oxidation ponds; but rather represents large growths as reported in various articles in the literature. Examination of these organisms indicates that the algae belong in three general groups; the motile algae, the non-motile small algae, and the filamentous algae. The motile algae have the ability to move and compensate for varying light conditions. Euglena and Chlamydomonas are the most frequent motile algae in oxidation ponds. Chlorella and Scendesmus are small, non-motile algae that present a large surface area to mass ratio so that they remain suspended with very slight fluid motion. The primary filamentous algae found in oxidation ponds is the blue green algae, Oscillatoria. The filamentous algae tend to form floating mats that are undesirable in oxidation ponds as they block light transfer, mixing, and surface reaeration.

In contrast to the large amount of information available on the algae in oxidation ponds the amount of information related to the bacteria is very sparce. No real detailed bacteriological studies have been made on them. Gann et al (48) made a laboratory study of the bacteriology of oxidation ponds and found Achromobacter, Pseudomonas, Flavobacterium, Bacillus, and coliforms. Approximately, 90-95% of the bacteria belong to Achrombacter, Pseudomonas, and Flavobacterium. They found that the coliforms died off as the BOD was reduced. Most of the primary bacteria activity occurred around the influent where the organic matter was being added to the ponds.

Observations of existing ponds and biochemical data would indicate that the normal soil and enteric bacteria are carried into the pond. The overall environment determines which bacteria grow and to what extent. It appears that anaerobic bacteria grow where the organic solids have settled near the influent. Methane production in highly loaded ponds indicates that methane bacteria are present. In heavily loaded oxidation ponds, the presence of hydrogen sulfide could mean the presence of the Desulfovibrio, sulfate reducing bacteria. The lack of nitrates in the oxidation pond effluents would indicate the presence of very few, if any, nitrifying bacteria. Most oxidation ponds show denitrification where nitrates are present in the influent. The prime concern with the bacteriology of oxidation ponds has been more related to the survival of enteric bacteria and potential survival of pathogenic bacteria. This public health aspect of oxidation pond bacteriology has overshadowed the microbiology concerned with waste stabilization. In all probability the bacteriology of oxidation ponds is similar to the bacteriology of other aerobic and anaerobic waste treatment systems.

Fungi are related to bacteria and are found in soil. It would be reasonable to expect fungi to be present in oxidation ponds,but the question could be raised as to their significance. Cooke and Matsuura (49) made a study of the oxidation pond near Lebanon, Ohio. Yeast were the primary group of fungi in the liquid phase with some filamentous fungi in pond sludges and floating scum. The difficulty in determining quantitative counts with fungi makes evaluation of the role of fungi difficult. While fungi are able to grow in oxidation ponds, there is no information available to indicate that fungi play a significant role in stabilizing the organic matter in oxidation ponds. Their role is secondary to the bacteria.

Viruses have stimulated interest from their possible public health standpoint like the enteric bacteria. Few studies have been made with virus because of their extreme specificity and the difficulty in quantitative measurements. In 1966 Christie (50) reported on a study with polio virus. It was demonstrated that oxidation ponds were capable of reducing the polio virus. Mixing the virus with raw sewage or with a pure culture of *Chlorella* showed that these materials were not toxic to the virus. Nupen (51) carried out extensive viral studies at the Windhoek treatment plant in South West Africa. Polio virus was also used in this study. Maturation ponds showed better than 95% virus reduction with only 14 days retention. Chlorination was definitely able to produce a viral free water after tertiary treatment (33).

Microscopic animals also occur in oxidation ponds. As in other waste treatment systems, the microscopic animals play a secondary role, feeding on the bacteria and the algae. Wennstrom (8) reported extensively on the microscopic animals in his 4 pond system. The protozoa predominated from October to March during the cool weather. Multicelular animals grew readily during the remainder of the year. *Vorticella* was the major stalked form of protozoa while *Paramecium* was the primary free swimming ciliated protozoa. *Glaucoma* and *Euplotes* were present in large numbers as was *Colpidium*. Rotifers and the crustacean, *Daphnia*, were very active in the summer months. At times the *Daphnia* ate most of the algae in the final pond, producing an effluent essentiall free of algae. The crustaceans also received the attention of Loedolff (52) at Pretoria, South Africa. The *Cladocera*, *Moina*, was found to remove *E. coli* at a faster rate than *Daphnia*. While these crustaceans were able to remove bacteria from wastewater systems, it was felt that the protozoa and rotifers were more efficient and hence, more significant. *Daphnia* appear to feed on algae when long retention periods are available for their growth. Usually, the *Daphnia* are able to clarify the pond of algae provided the food level is low. The *Daphnia* will not remove all of the algae in primary ponds where the algae have enough food for rapid growth. There is no doubt that the microscopic animals can play an important role in reducing the algae population in the final effluent. The study by Wennstrom (8) showed that when the *Daphnia* predominated in the final pond, an effluent BOD of essentially zero was produced. To date, the design of oxidation ponds in the United States have not attempted to utilize the algae removal capabilities of these crustaceans. Their growths have been noted from time to time as an example of a strange, uncontrolled, biological growth. In isolated areas where land was readily available, *Daphnia* could produce a high quality effluent without any special operational requirements, especially in the warmer sections of the United States.

A highly specialized group of microorganisms that are sometimes found in oxidation ponds are the purple sulfur bacteria. The purple sulfur bacteria are photosynthetic bacteria that grow similar to algae. In the presence of sunlight, carbon dioxide and hydrogen sulfide the purple sulfur bacteria are able to grow and oxidize the hydrogen sulfide. Needless to say, these highly colored bacteria will occur only at the surface of very heavily loaded oxidation ponds. This is the reason why the purple sulfur bacteria are treated separately from the normal bacteria in oxidation ponds. Because of their unusual color, the purple sulfur bacteria have attracted considerable attention. Cooper *et al* (22) found *Thiopedia* in a pond treating rendering wastes and *Chromatium* in another pond treating petroleum wastes. Parker (37) also found *Chromatium* in an oxidation pond loaded in excess of 1000 lbs BOD/acre/day. Holm and Vennes (53) identified three genera of purple sulfur bacteria in North Dakota lagoons receiving potato processing wastes together with domestic sewage. *Thiocapsa* was the predominant organisms when acetate in the lagoon reached 1000 mg/l. Over 90% BOD reduction was obtained during the period when the purple sulfur bacteria predominated. Normally, the purple sulfur bacteria do not grow in properly designed and operated oxidation ponds; but it is important to recognize that their presence in an oxidation pond is definite evidence of overloading and the production of hydrogen sulfide.

The microorganisms that grow in any oxidation pond are a function of the organic matter in the wastes, the retention time, mixing, and other environmental factors. The success or failure of the oxidation pond as a waste treatment device depends upon the biochemical reactions that the microorganisms produce. For this reason it is important not only to know which microorganisms occur but also to know the reactions that each group of microorganisms produce.

Biochemical Reactions:

There are two primary biochemical reactions and one secondary biochemical reaction in normal oxidation ponds. As shown by Oswald and Gotaas (3) the bacteria metabolise the organic matter with the production of bacteria and stable end products. With adequate oxygen the end products are carbon dioxide, water, ammonia, and phosphates. The algae can utilize these end products of bacterial metabolism in the presence of sunlight to synthesize more algae with the release of the excess oxygen. The bacteria derive their energy for cellular synthesis from the oxidation of a portion of the organic matter in the wastes and conversion of the remainder of the organic matter to new cells. On the other hand, the algae use light energy to reduce the oxidized end products of bacterial metabolism to cellular protoplasm. The reduction reaction results in a release of oxygen which can be used by the bacteria. This general reaction formed the basis for oxidation pond operation for many years with little regard to the quantitative aspects of any of the biochemical reactions.

Oswald et al (54) attempted to put quantitative relationships onto the algae-bacteria symbiosis that occurred in oxidation ponds. The maximum bacteria population occurred in domestic sewage at 1.5 days, approximately 10^8/ml. *Euglena* was the algae used since it occurred in most oxidation ponds. It was found that optimum growth of *Euglena* occurred at 400 ft-candles of light although there was little variation up to 1200 ft-candles. Chemical analyses of Euglena gave an empirical formula of $C_{7.62}H_{8.08}O_{2.53}N_{1.0}$. The metabolic equation for algae growth was set forth:

$$1.0NH_4^+ + 7.62CO_2 + 2.53\ H_2O \longrightarrow C_{7.62}H_{8.08}O_{2.53}N_{1.0} + 7.62O_2 + 1.0OH^+$$

The ratio of carbon dioxide consumed to oxygen produced was 1.0. This was similar to that reported in the literature with algae grown in pure culture on simple substrates. The growth of algae followed the growth of the bacteria since the algae used the carbon dioxide produced by the bacteria. One significant factor that has been overlooked by many engineers was the fact that carbon was the limiting factor in the growth of algae in sewage oxidation ponds.

Studies summarizing the metabolism of algae have been reported by Fogg (55). He stated that the algae metabolism was as follows:

$$CO_2 + 2H_2O \longrightarrow (CH_2O) + H_2O + O_2$$

Fogg felt that the algae used free carbon dioxide only and produced carbohydrates which were further metabolised to form algae protoplasm. He, too, analysed algae and presented the following metabolic equation for the growth of algae:

$$1.0\ NH_3 + 5.7\ CO_2 + 3.4\ H_2O \longrightarrow C_{5.7}H_{9.8}O_{2.3}N + 6.25\ O_2$$

The quantity of oxygen produced by this equation is actually greater than the carbon dioxide consumed, giving an increase in oxygen production over that normally expected. The weight of oxygen produced per unit weight of protoplasm produced was 1.55 gm O_2/gm vol. algae mass by Oswald _et al_ (54). Yet, there was a definite difference in the formulation of the algae. A recent study by Richardson _et al_ (56) on _Oocystis_ and _Chlorella_ found the empirical formulation of two pure culture analyses averaged $C_{5.3}H_{9.4}O_{2.7}N$. It would appear that the formula originally presented in Fogg (55) is the probable empirical formula for algae grown in oxidation ponds. Richardson _et al_ (56) found the caloric value of 5.9 Kcal/gm vol. algae mass for _Chlorella_ and 6.2 Kcal/gm vol. algae mass for _Oocystis_. This checks quite close to the caloric value for bacteria reported by Payne (57).

Oswald _et al_ (58) observed that 3.68 calories of energy were required by algae to produce 1.0 mg/l of oxygen. This value was confirmed by Richardson _et al_ (56). It has been indicated that algae can convert approximately 10 percent of the light energy into the creation of new cells. Since the growth of algae and the resultant oxygen production are related to the use of light energy, more oxygen will be produced in the summer than in the winter in odixdation ponds.

A study of the biochemical reactions as they exist in field ponds was carried out by Bartsch and Allum (59) in South Dakota. They used light and dark bottle studies to examine the oxygen production and respiration as it actually occurs in oxidation ponds. The growth of algae results in suspended solids that block the light and prevents its penetration. Thus, the more algae that grow, the less light there is for further growth. It also means that growth is pushed closer to the surface of the pond. In July, 1955, 99% of the light reaching the surface of the oxidation pond at Kodaka, South Dakota, was absorbed in the top 15 inches. At Lemmon, South Dakota, 99% light absorbance occurred at 32 inches. They found that the Lemmon oxidation pond produced 2.9 mg/l O_2/hr at 1050 ft-candles of light, 0.4 mg/l O_2/hr at 167 ft-candles, 0.1 mg/l O_2/hr at 27 ft-candles, and 0.04 mg/l/hr at 3.8 ft-candles. Stabilization of the sewage added to the oxidation pond produced a uniform oxygen demand rate of 0.04 gm/m^2/hr. The total microbial respiration rate was 0.7 gm/m^2/hr. Thus it was that the algae created an endogenous respiration oxygen demand 17 times greater than the microbial oxygen demand for stabilizing the sewage. This clearly indicated that the algae growth was related to something more than stabilized sewage.

Towne et al (60) commented further on the data collected in the previous study (59). They indicated that wind action across the surface of the oxidation pond is important in carrying the oxygenated water to the lower depths; but this same wind action accelerated the loss of oxygen to the atmosphere. Supersaturation of the surface of the oxidation pond with oxygen reached as high as 43 mg/l. Loss of this oxygen to the atmosphere meant that some algae would not have enough oxygen for complete endogenous respiraton. Bartsch (61) indicated that the production of 1.6 pounds of oxygen in the oxidation pond resulted in the creation of 1.0 pound of volatile algae mass. Thus, lots of algae were produced for every pound of BOD stabilized in the oxidation pond. These algae had an oxygen demand that had to be satisfied. In effect, he recognized that the oxidation pond was transforming the organics from their original form in sewage to a new form as algal cells. The question was raised as to the desirability of such a conversion.

Research into the algae metabolism by Stoltenberg (62) indicated that Chlorella could produce 1.22 moles O_2/mole CO_2 utilized at low carbon dioxide concentrations. On the other hand, endogenous respiration produced one mole CO_2/mole O_2 utilized. The rate of endogenous respiration was 11.2 mg/l/hr/1000 mg/l algae at 25°C, approximately the same as bacteria. The data indicated that approximately 18 percent of the algae mass was not biodegraded by endogenous respiration. Nelson (63) examined the endogenous respiration of the algae bacteria mixture in greater depth and found that the endogenous respiration rate was related to the metabolism of carbohydrates first and proteins second. The overall endogenous rate for the protein fraction was 1.8%/hr while the carbohydrate fraction was metabolised at a faster rate. The rate of oxygen production was found to occur from 14 to 60 times as fast as the endogenous respiration rate. Algae have the ability to produce oxygen very rapidly and can use both bicarbonates and carbonates as sources of carbon as well as carbon dioxide. In the light algae use the carbon dioxide from the endogenous respiration as fast as it is given off; but in the dark the algae can exert a large oxygen demand rate. Nelson demonstrated that the algae definitely had an inert organic cell mass residual that was not metabolised the same as bacteria.

While the symbiosis between the bacteria and algae was recognized, the concepts of oxidation ponds were still looked at as a simple aerobic system in which the aerobic bacteria stabilized the organic matter and the algae produced the oxygen needed for the aerobic reaction. Few engineers recognized that the suspended solids in raw sewage settled out close to the inlet, creating a sludge blanket. Most of the early concern for settleable solids was with loss of oxidation pond capacity. Little concern was shown for metabolism of those settled solids. It was just assumed that these settled solids underwent aerobic matabolism until data were collected to show that the oxygen concentration at the bottom of most oxidation ponds were devoid of oxygen essentially all of the time. This meant simply that the settled solids were undergoing anaerobic metabolism rather than aerobic metabolism. Oswald (64) recognized that anaerobic conditions developed in normal oxidation ponds and resulted in removal of some of the BOD load. He indicated that at low temperature, 4°C, or at low pH, under 5.5, the biological metabolism ceased. Thus, during the winter months in the northern states the settled organic matter is stored until the weather warms up. This is a very important reaction in oxidation ponds located in cold weather regions. When the bacteria degrade the organic solids anaerobically, organic acids are produced which diffuse slowly into the liquid layer above the settled solids. If the organic acids build up too much the pH will drop and stop further metabolism. If sulfates are present in the water around the solids, sulfate reducing bacteria can grow up with the production of hydrogen sulfide that diffuses into the upper layer of water in the pond. If excess organic matter still remains methane bacteria can buildup and produce considerable quantities of methane that is lost to the atmosphere. Oswald et al (31) studied the oxidation pond at Concord, California and found that 8-10 cu.ft. of gas was produced from each pound of volatile solids added. Approximately 20% of the organic solids added to the pond underwent methane fermentation, the rest remained as inert organic matter. The gas produced was essentially methane with little carbon dioxide. As the temperature dropped below 16°C, methane production essentially ceased. Thus, methane bacteria can play a role in stabilizing a portion of the organis added to the ponds.

The bacteria in the oxidation pond are responsible for stabilizing the organic matter in the liquid phase as well as in the solid phase. Those bacteria in the liquid above the sludge are able to metabolise aerobically as long as there is dissolved oxygen. Hoover and Porges (65) analysed bacteria protoplasm and found that the empirical formula for bacteria was $C_5H_7O_2N$. A number of other empirical formula have been proposed but they generally represent materials other than living bacteria. Eckenfelder and O'Conner (66) reported that the caloric value of activated sludge grown on skim milk was 5.7 Kcal/gm. By and large efforts to develop simple thermodynamic data on the metabolic reactions of bacteria in wastewater have not been too successful. Endogenous respiration has produced a secondary reaction that made determination of the synthesis reaction difficult. McKinney (67) followed up earlier work that showed a relationship between BOD and cellular synthesis and developed a basic metabolic concept. He postulated that 1/3 of the energy contained in the organic matter being metabolised would be oxidized to yield the energy to convert the remaining 2/3 to cell mass. This was the synthesis reaction. Endogenous respiration resulted in oxidation of the remaining cellular energy. In terms of maximum synthesis 0.47 gm dry weight vol. bacteria mass would be produced for each gm of ultimate BOD metabolised by the bacteria. Payne (57) reported 62% of the enthalphy was conserved as cell mass in comparison to 67% as indicated by McKinney. Servizi and Bogan (68) disputed the validity of the 1/3-2/3 relationship and related synthesis to the free energy of oxidation. They followed up with data (69) to show that activated sludge systems had a synthesis yield of 0.39 gm dry weight vol. bacteria mass for each gm of COD metabolised as carbohydrates and 0.35 gm vol. mass/gm COD as aromatics and aliphatic acids. Since Bogan and Servizi failed to consider endogenous respiration as a factor in evaluating their data, their synthesis-energy values are low. The complexity of the energy relationships as proposed in the current literature is such that engineers concerned with biological treatment plant design have ignored most of the relationships as they cannot measure the basic parameters. The exact 1/3-2/3 relationship proposed by McKinney may not be absolutely precise but is within experimental error for treatment plant design and makes a useful tool. In terms of 5 day BOD the synthesis reaction requires a minimum of 0.5 lb O_2 for the production of 0.7 lb vol. mass from 1.0 lb BOD. Endogenous respiration increases the oxygen demand and reduces the cell mass proportionally as time proceeds. In oxidation ponds the retention period is very long so that endogenous respiration becomes significant.

Kountz and Forney (70) studied endogenous respiration in biological systems and found approximately 20% of the activated sludge produced was non-biodegradable. The fact that 1/5 of the vol. mass does not undergo oxidation means that only 4/5 can be oxidized. The net result is that only 87% of the ultimate BOD can be exerted in a biotreatment system. The remaining

13% of the ultimate BOD is essentially inert in the aqueous environment. It probably is degraded very slowly, too slowly to be significant in treatment plant design or operation. In effect, the maximum amount of oxygen required by the BOD in domestic sewage would be 1.3 lbs/lb of BOD stabilized. This is the amount of oxygen which the algae must produce unless some of the BOD is removed by sedimentation and methane fermentation. With domestic sewage approximately 50% of the BOD is in the form os suspended solids which will settle out in an oxidation pond.

The settleable solids in domestic sewage are only partially degradable. Approximately, 40% of the volatile suspended solids fraction is non-biodegradable. Couple this non-biodegr-dable organic fraction with the inorganic fraction and you have essentially 50% of the settleable solids that can undergo decomposition even under favorable conditions. It is not surprising to note that the settled solids in oxidation ponds do not undergo rapid metabolism. These s solids settle out close to the inlet structure with each new load of solids settling over the previous solids. The new solids act as a blanket that retards further metabolism of the settled solids. In an effort to examine the oxygen demand rate of settled sludge, samples were studied in the Laboratory by McKinney and Benjes (71) to determine some of the basic factors affecting metabolism. As expected, the rate of metabolism was found to be a function of diffusion of anaerobic end products into the aerobic upper layer where they could be oxidized. As the rate of fluid flow over the top of the sludge increased, the rate of oxygen demand increased. Thus, mixing becomes very important in stabilization of the settled solids. Since most oxidation ponds have little movement of water over the surface of the settled sludge, the rate of metabolism becomes limited by that water movement and simple molecular diffusion. One could expect 10-20% of the settled BOD to be exerted in lightly loaded oxidation ponds and less in more heavily loaded ponds. The remaining organic matter will be preserved by the low pH of the organic acids or converted to methane. Some sulfate reduction could take place but it would be limited to the available sulfates trapped in the water with the solids. It appears that most oxidation ponds will require only 0.8 lb oxygen/lb BOD when the raw wastes are domestic sewage. Soluble industrial wastes can be expected to demand the full oxygen load of 1.3 lb O_2/lb BOD.

It has been indicated the algae use the carbon dioxide produced by the bacteria for metabolism. Examination of the characteristics of domestic sewage indicates that 87% of the oxygen utilized is for the oxidation of carbon while the remaining 13% of the oxygen required is for oxidation of hydrogen. This means that the bacteria are going to demand more oxygen than will be released by the algae if the algae have an RQ of 1.0 as indicated in the literature. It has been suggested that the extra oxygen could be supplied by surface aeration. Examination of field data indicates that a significant quantity of the oxygen produced by the algae is actually lost to the atmosphere, making the situation even worse. It appears that the algae metabolise the bicarbonate alkalinity in the water as well as the carbon dioxide produced by the bacteria.

Normal domestic sewage will contain close to 300 mg/l bicarbonate ions together with approximately 30 mg/l carbon dioxide. The carbon dioxide will be metabolised by the algae first and then the bicarbonate will be metabolised. As the bicarbonate is metabolised, the pH increases and a portion of the bicarbonate is converted to carbonate. As the pH rises to the point where significant hydroxide alkalinity is formed, toxic conditions result and further metabolism ceases. It appears that approximately 10 mg/l hydroxide alkalinity is toxic to the algae, making pH of 10.3 about maximum. In hard water the calcium ions will precipitate and remove the carbonate ion concentration down to 30 to 40 mg/l At pH 10.3 there would be approximately 27 mg/l bicarbonate left unmetabolised. The 270 mg/l of bicarbonate that was removed was converted to carbon dioxide and carbonates. There would have been 135 mg/l carbonate formed. Approximately 100 mg/l of the carbonate ion would have been precipitated with 67 mg/l calcium. There would still be 25 mg/l of calcium left in solution. Since phosphate tends to precipitate at pH values above 9.0, an additional 25 mg/l of calcium would have been removed with the phosphate precipitate. Few sewages have 120 mg/l calcium for maximum precipitation. The net result is that some of the carbonate will remain unprecipitated as will some of the phosphate.

With normal domestic sewage one can expect that 52 mg/l of carbon would be released as carbon dioxide from the stabilization of the BOD. Maximum utilization of the bicarbonate carbon as indicated in the previous section would yield an additional 27 mg/l of carbon. If the algae were able to metabolise all this carbon, they would form approximately 160 mg/l VSS of new algae and release 210 mg/l of oxygen. Since the bacteria only need 160 mg/l of oxygen for stabilization, there is an apparent surplus of oxygen. But it must be recognized that the algae formed have a potential oxygen demand of their own that must be satisfied. If the algae were completely metabolised, approximately 20% of the cell mass would remain unmetabolised the same as bacteria. The 160 mg/l VSS of algae would need 180 mg/l for endogenous respiraton. Since only 50 mg/l of oxygen is available, there would be a deficit of 130 mg/l of oxygen. This oxygen deficit is currently being satisfied by one of two methods, sedimentation of algae prior to complete endogenous respiration or discharge in the effluent. The high effluent suspended solids in some oxidation ponds indicates that a considerable quantity of the algae is being lost to the receiving stream and the oxygen burden is being transferred to downstream areas. With multiple ponds the algae are retained in the oxidation pond system through sedimentation and a satisfactory effluent quality is produced.

The rate of metabolism becomes a very important factor in the oxidation pond the same as in any biotreatment system. In effect, the oxidation pond operates in the same fashion as the BOD bottle. The bacteria are essentially maintained in a dilute, dispersed condition and are limited in their ability to obtain organic matter. It can be expected that all of the soluble organic matter in the raw sewage would be oxidized within 20 days at 20°C. This would mean that the bacteria converted all of the organic matter to new cell tissue in 2 to 3 days with endogenous respiration and predation by protozoa, rotifers and crustaceans accounting for the remaining oxygen use over the next 18 days. Increasing the temperature to 30°C would permit stabilization in 10 days instead of 20 days while a decrease in temperature to 10°C would require 40 days and to near 0°C would require 80 days.

The response of the algae is similar to the bacteria except that the algae can continue to grow in the light and recycle their carbon as fast as it is released by endogenous respiration. It appears that the rate of endogenous respiration will be around 1.0-2.0%/hr on a uniform basis at 20°C. The inert organic matter related to the algae will accumulate at the rate of approximately 5% per day so that the turnover time of the algae will be around 20 days. The accumulation of the inert fraction of algae reduces the ultimate oxygen demand on the receiving stream. Thus, it is then that longer retention period oxidation ponds not only permit the algae to settle but also allow the algae to recycle adequately to accumulate enough inert organic matter to yield an excess of oxygen for the stabilization reaction in the oxidation pond. Since the carbon dioxide from the algae can be reused, it follows that the maximum crop of 160 mg/l VSS of algae would be reduced to 128 mg/l in 20 days, 102 mg/l in 40 days, 82 mg/l in 60 days, 66 mg/l in 80 days, 53 mg/l in 100 days and 42 mg/l in 120 days by endogenous respiration alone without any sedimentation. At temperatures lower than 20°C the rate of endogenous respiration decreases. The temperature factor decreases by two for each 10°C temperature drop. It follows that the effluent BOD from the oxidation pond system will be related to the endogenous respiration of the algae mass discharged. It can be estimated that the BOD of the algae will be 0.75 mg/l for each 1.0 mg/l living cell mass, VSS. It can easily be seen that without some form of algae separation, a high quality effluent in terms of BOD or suspended solids could not be produced from an oxidation pond.

The previous evaluation was based on complete metabolism of available carbon. It must be recognized that all of the carbon is not available for photosynthesis. Without mixing the algae would build up at the surface of the oxidation pond and block light penetration. It appaers that the upper 10 to 15 inches in the pond will be actively photosynthesizing if the data presented by Oswald (64) is correct. If it is assumed that only the top foot of the oxidation pond is active photosynthetically, the algae production in a 4 ft pond would be reduced by a factor of four without mixing. Since algae production is essential for adequate oxygen, mixing is a must. Wind action is responsible for mixing in most ponds. Where the pond detention time is long enough, 60 days or more, wind action is adequate. In oxidation ponds having short detention times, wind mixing may not be adequate and some form of mechanical mixing may be necessary to produce maximum algae production. Care must be taken with mechanical mixing devices as too much agitation at the surface will result in loss of oxygen to the atmosphere rather than retention for the microbial reactions.

Thus, the primary biological reactions occurring in the oxidation pond are the bacteria stabilizing the organic matter and then undergoing endogenous respiration and the algae producing oxygen and algae from inorganic carbon sources and undergoing endogenous respiration. The bacteria are not light dependent but the algae are. These facts tell the engineer why proper lighting and mixing are so important to the proper functioning of the oxidation pond. The secondary biological reactor is the consumption of bacteria and algae by protozoa, rotifers, and crustaceans. These microscopic animals are strict aerobes and will grow best in the upper layers where the algae have produced a good food source and adequate oxygen. The bacteria and the algae grow more rapidly than the microscopic animals, permitting maintenance of all forms when mixing is adequate. Occasionally, the crustaceans have metabolised all of the algae in the final cell of multicell ponds when mixing is minimal. Normally, metabolism of the available algae will result in loss of the available food supply for the crustaceans and they will soon die off and the algae will reappear. To date, it has not been possible to design oxidation ponds to take advantage of the ability of the crustaceans to remove the excess algae from the oxidation pond effluent. While the crustaceans would have removed the algae, they in turn would exert a BOD which would have to be satisfied eventually.

Design Relationships

The basic biochemical reactions form a basis for the development of sound design relationships. It can be seen that the bacteria stabilize the organic matter very rapidly, 1-2 days in the summer and 8-10 days in the winter, provided they have adequate oxygen for metabolism. The bacteria then undergo slow endogenous respiration. In effect, the bacteria then would be completely stabilized in 20 days at 20 C under aerobic conditions. Atmospheric diffusion could be expected to meet the oxygen demand of the bacteria with a retention period of 80 days with little mixing and in a shorter period with good mixing. The growth of algae precludes the construction of a simple bacteria pond. The algae respond to the environment created by the bacteria and the wastes and grow. Normal domestic sewage will permit synthesis of 160 mg/l VSS as algae provided there is good mixing. With poor mixing only the upper 12 inches of the oxidation pond will have 160 mg/l algal mass. Diluting this algae with the total effluent would give an algae concentration of only 40 mg/l. Wind mixing normally permits the algae synthesis in the pond to be between 40 mg/l and 160 mg/l. Synthesis of 100 mg/l of algae would meet the oxygen demand of the bacteria. Most oxidation ponds can produce algae as fast as the carbon dioxide becomes available from the bacteria. Theoretically, a 20 day retention period pond with a depth of 4 ft could satisfy the oxygen demand of the bacteria. The only problem is separating the algae from the liquid. Endogenous respiration and protozoa predation are needed to reduce the algae concentration to a reasonable level. A 20 day retention period for normal domestic sewage would give a BOD load of 108 lbs/acre/day. Research at Fayette, Mo. (11) demonstrate that a BOD loading of 120 lbs/acre/day produced adequate algae growth to maintain dissolved oxygen except at low temperatures when ice covered the ponds. Based on BOD loadings and changes in the alkalinity the daily oxygen demand of 200 mg/l in the summer was satisfied by the production of 220 mg/l oxygen from the daily growth of 170 mg/l algae. At 20°C the average algae mass in the oxidation pond would have been 137 mg/l with 20 days retention and the effluent BOD would have been approximately 100 mg/l. The actual BOD was lower than this as the result of algae settling in the pond. Examination of the organic nitrogen data indicated that 83% of the algae had been removed by sedimentation. If this were the case, the expected BOD would have been 18 mg/l. The measured BOD in July was 23 mg/l. It appeared from the Fayette data that the theoretical BOD relationship with regard to organic nitrogen in algae cells checked very close to 8.6 mg/l BOD for 1.0 mg/l organic nitrogen. The 10 month average organic nitrogen concentration in the heavily loaded pond from the Fayette study was 6.6 mg/l, giving a predicted BOD of 57 mg/l against an average measured BOD of 53 mg/l. This indicates that the organic matter in the wastes were stabilized by the algae in accordance with the biochemical concepts presented in the previous section and that the effluent quality was strictly a function of algae separation. The second oxidation pond in series received only the algae from the first pond. Endogenous respiration and sedimentation reduced the organic nitrogen in the effluent to 2.4 mg/l, giving a predicted effluent BOD of 21 mg/l against a measured average of 26 mg/l. Closer results cannot be expected from field data.

The problem in oxidation pond design lies in algae separation and temperature effects. As long as ice is not a factor to block the algae from obtaining adequate light, a 20 day retention period is adequate for waste stabilization of domestic sewage even in cold weather. Ice formation blocks the light from reaching the algae and prevents development of adequate oxygen for the bacteria to continue metabolism until the algae return. As long as the ice covers the oxidation pond, the anaerobic end products that create the obnoxious odors are held in the liquid and can only be lost in the effluent. When the ice melts and spring winds create rapid mixing, the anaerobic end products which have been produced are released to create nuisance conditions in the immediate vicinity of the oxidation pond. These nuisances persist until the algae create enough additional oxygen to satisfy the extra demand. This explains why the more heavily loaded oxidation ponds take longer to recover from winter operations than lightly loaded oxidation ponds. Artifical aeration during the winter months can satisfy the oxygen demand under the ice if odor nuisances are critical problems. When the ice melts and the algae have returned to a satisfactory level, the artificial aeration system can be discontinued until the ice cover returns. During winter operations bacteria can stabilize the organic matter easily within the 20 day retention period but complete endogenous respiration of the bacteria would require almost 80 days at 0°C. The effluent quality in the winter period is related then to both anaerobic end products and the bacteria remaining. Where a high quality effluent must be produced in the winter months, artificial aeration will be a necessity. Even with artificial aeration, bacteria separation will be required the same as algae separation is required during the remainder of the year.

Very little research has been carried on for algae separation in small ponds with a minimum of operational skills and equipment. For the most part it has been shown that centrifugation and chemical precipitation can remove the algae and produce a quality effluent. Unfortunately, both are far boo complex to use in the majority of oxidation pond installations. The best method to date for algae separation in the field appears to be multicell ponds. Not only do multicell ponds reduce the short circuiting of wastewater flow through the oxidation pond; but they permit some effective seaparation of algae by the use of subsurface drawoffs. The important aspect of multicell design is the outlet structure. The outlet structure is designed to draw final effluent from below the surface of the oxidation pond. In this way the heavy algae growth at the pond surface is avoided. In the past the multicell ponds have been designed on the basis of total pond voluem as the treatment unit. Actually, the first pond is the treatment unit and the remaining cells are merely solids separation ponds. If maximum solids separation is to be desired, minimum mixing is desired. Since mixing is important in the treatment unit, it can be seen that a single cell oxidation pond is a poor design as far as treatment is concerned. In the bacterial reactor there is a need for limited mixing to keep the oxygen and the bacteria together with the soluble organics to be metabolised. Actually, the mixing should not be such that the heavy solids in the raw wastes are kept in suspension. This intermediate degree of mixing is difficult to achieve when natural wind action is the basis for mixing. In the other ponds, mixing is not needed and is undesirable.

If multicell ponds are to be used for algae separation, it appears that the first cell should be designed for 20 days retention on an average flow rate to permit variations in organic load to be easily absorbed and to permit good operation in the winter period under ice cover. The first pond should be designed with a 4 ft normal depth to give maximum surface area for photosynthesis. The inlet should be designed to give a circular, deeper, sludge storage zone below the bottom of the normal pond. This will allow maximum wind mixing to occur without stirring up the settled solids. The sludge storage section should have a maximum diameter of 100-200 ft with a center depth of 4 to 6 ft. The taw waste inlet pipe should be located in the center of the sludge storage section so that the raw wastes enter the pond in a radial fashion to distribute the load around the inlet pipe in the same fashion that inlet structures are designed for circular clarifiers except that all of the baffles in the oxidation pond should be submerged. This will permit the heavy solids to remain around the inlet and undergo anaerobic decomposition with a minimum oxygen demand. The outlet from the first cell should have the capacity to change the depth from 3 to 5 ft in 6 inch increments to give operational flexibility as well as a drain for the entire pond. The outlet structure should be designed to minimize fluid velocities at a single point. In small plants a large pipe outlet with adjustable sections is adequate. In large plants an adjustable weir will be required. There should be three sets of baffles concentrically around the effluent structure. The first baffle should be designed to extend around the outlet structure 3-5 ft with the baffle extending at least 6 inches to one ft above the highest water level and down to within one foot of the bottom of the pond. Thus, the effluent will be drawn from the bottom of the pond. The second concentric baffle rises from the bottom of the pond to within 6 inches of the surface at the lowest possible level. The third concentric baffle is the same as the first, rising above the maximum surface and dropping to within one foot of the bottom of the pond. These baffles are designed to give an up and over type baffle with a bottom drawoff to minimize removal of algae from the active zone and to allow the algae to congregate at the surface within a quiescent ring that is not affected by wind action. In effect, a stilling basin is created which encourages the algae to accumulate at the light surface and minimizes mixing to interfere with sedimentation. The addition of 1-2 inch rock to a depth of two feet around the outlet structure out to the second baffle will give filtering surfaces that will increase the algae removal even further.

The second pond should be designed for algae removal. Mixing dur to wind action should be minimized. The small particle size and the low specific gravity of algae prevent rapid removal. The size of the pond depends on the extent of endogenous respiraton desired. The reuse of carbon dioxide produced by endogenous respiration limits the size of the second ponds or additional ponds. To produce a quality effluent from endogenous respiration alone, the ponds would need a total retention period of 120 to 160 days. A small second pond can be used as easily as a large second pond or a series of ponds, if the algae can be removed. Use of a small second cell requires that the algae be removed by rock filtration as suggested by Martin (36) or possibly killed with chlorine and allowed to settle or chemically precipitated. Further research is need on this topic. There appears to be limited benefit from more than three cells in series although the wastewater flow through time will be better in multicell units than in a single unit. This is very important in coliform reductors.

Coliform reductions and pathogenic bacteria reduction does not result from a toxic environment or any unusual predation. The die-off of coliforms and any bacteria follow the same general patterns. As indicated by theory, the organic matter is essentially removed in 2 days so that there is limited food for the microbes to metabolise and to stay alive. The net result is that the bacteria die off. The bacteriological data collceted to date (8,37,41,42) confirms the coliform dieoff follows expected patterns with detention period being the predominant factor and temperature a secondary factor. The coliform dieoff appears to follow normal endogenous respiration rates with slower metabolism at the lower temperature and hence greater survival rate. At 20°C the dieoff of coliforms and the enteric bacterial pathogens should give 99% reduction in 20 days, 99.99% reduction in 40 days, and 99.9999% reduction in 60 days provided there is no short circuiting. A single cell pond will show considerable short circuiting, depending upon the wind mixing. To maximize the dieoff of bacteria a large number of cells with minimum mixing is required. Needless to say, it is not possible to achieve a high degree of bacteria removal with retention periods under 100 days with conventional two cell ponds. Chlorination will be required to produce a high degree of bacterial reduction. If chlorination is to be used in oxidation ponds, it might as well be used to kill the algae as well as the bacteria as some kill will result. By constructing a small cell with the oxidation pond or by a separate pond having two days retention and surface baffles to retard mixing, it is possible to chlorinate the algae-bacteria mixture and kill both the algae and the bacteria. The two day retention period pond will allow the algae to settle and will produce a satisfactory effluent. The dead algae will be allowed to accumulate in the small pond and will not exert as great a BOD in the receiving stream as would be the case if the algae are chlorinated as the eflfuent leaves the oxidation pond. The rock filter would also be of value in removing the dead algae in the chlorination pond.

There is no doubt that oxidation ponds as currently designed will not meet future water quality criteria. In this the critics are right. But examination of the fundamental microbiology and biochemistry together with engineering concepts indicates that there are solutions to the oxidation pond effluent quality problem without major changes in concepts. Short time pond systems are possible if the algae are removed. Long retention periods are required if a high quality effluent is to be produced naturally. A number of design modifications were suggested based on limited small scale research or on extrapolation of available field data and the fundamentals. These concepts should be tried in demonstration projects as soon as possible so that the value of these modifications can be ascertained. It is essential that every effort be made to obtain the maximum capability from the oxidation pond systems. They remain on the simplest wastewater treatment systems to design, construct, and operate. In view of limited skills for the future in the area of wastewater technology, oxidation ponds must be kept as simple as possible while attaining the deisred results.

In recent years researchers and engineers have attempted to mathematically evaluate oxidation ponds so that a series of design equations could be available to the engineer. For the most part these design equations were developed from laboratory models or field data without careful examination of the fundamental reactions occurring within the ponds. The net result was that the various design models fitted the data at hand but differed from each other and tended to create confusion rather than clarity in the minds of the design engineers. It is not surprising that engineers have ignored these design models in favor of the simplified design criteria based on field experience. Field experience has worked reasonably well. With the additional fundamental concepts to help the design engineer understand what is happening in oxidation ponds, it should be possible for the engineer to design oxidation ponds to produce any desired result.

DESIGN EXAMPLE

A domestic sewage has the following characteristics:

BOD = 200 mg/l
Suspended solids = 240 mg/l
Flow = 100 gpcd
Population = 10,000 people

Design an oxidation system to produce an effluent of 20 mg/l BOD and 20 mg/l suspended solids with (a) a minimum of mechanical equipment and with (b) mechanical equipment needed to minimize the pond size.

(a) Minimum Mechanical Equipment

It must be recognized that the 20 mg/l BOD is carbonaceous BOD only. It is assumed that the receiving stream has the ability to absorb the nitrogenous BOD. Since mechanical equipment is to be minimized, the pond retention period must be maximized. All of the effluent BOD and suspended solids will be related to the algae in the system. Actually the effluent suspended solids will control the design in this case.

The algae have 90% volatile matter in their cells,

Effluent VSS = 0.9 (20) = 18 mg/l
Effluent BOD = 0.75 (18) = 14 mg/l
Influent load: BOD_5 = 1670 lbs/day
SS = 2000 lbs/day

Design the system in multicell units having a 20 day retention each.

Cell volume = 20(1,000,000) = 20 x 10^6 gallons each
= 2.65 x 10^6 cf each
Cell depth = 4 ft.

Design the cell so that it is square.

Bottom length = 800 ft.
Top length = 824 ft.
Surface area = 680,000 sq. ft.
= 15.7 acres

Organic load on 1st cell = 1670/15.7 = 106 lbs BOD_5/acre/day
This BOD load is not excessive for the first cell.

Design a sludge retention section around the raw waste inlet.
Use a 200 ft diameter section 4 ft deep located in one corner.
Assume 95% suspended solids settling in this section.
Solids accumulation = 0.95(2000) = 1900 lbs/day.
Assume 6% solids concentration.
Solids volume = 500 cu ft/day
Sludge retention section volume = 125,000 cu ft.
Sludge retention without metabolism = 250 days.

Needless to say, the sludge retention period is too short for effective storage. The volume must be increased significantly. Because of the heavy solids load on the first cell, consider deepening the entire cell another 4 ft. for sludge storage.

Sludge retention volume = 2,470,000 cu ft.
Sludge retention without metabolism = 4,950 days
= 13.5 years
Assume 20% metabolism of biodegradable fraction of settled solids.
Expected sludge retention = approximately 15 years.

At the end of 15 years operation the sludge retention section should be full of sludge and should be removed and returned to the land. Additional anaerobic metabolism could reduce the solids and extend the life of the sludge retention section. Concentration of solids to 10% would extend the life of the sludge retention section to 25 years.

Influent pipe: Locate inlet pipe approximately 300 ft along the diagonal across the corners at the bottom. The inlet pipe should rest firmly on the bottom of the pond or should be below ground. The influent pipe should be attached to a concrete slab or anchor at end with a vertical riser above the pond surface approximately one ft and topped with a removable cap for cleaning. The discharge points from the influent pipe shall consist of a series of vertical slots, 6 inches long and 2 inches wide, around the pipe. The top of the slots shall be located 4 ft below the normal water surface, giving a discharge in the horizontal plane. The heavy solids would be expected to settle out within a radius of 100 ft. of the inlet. It may be necessary to periodically check the area immediately around the inlet for solids accumulation.

Effluent pipe: The effluent pipe between the first and second cells should be located near the opposite corner from the inlet pipe. The effluent pipe should be at least 24 inches in diameter and laid horizontally between the two ponds at a depth of 4 ft so that the pipe invert enters at the floor of the second cell. A 4 ft diameter circular steel baffle should be placed around the outlet pipe, going from the ground to one ft below normal water level. A second circular steel baffle 8 ft in diameter is placed around the 4 ft diameter baffle. The 8 ft diameter baffle should extend 2 ft above normal water level and extend into the ground. A single 12 inch diameter hole located 4 ft below the normal water surface permits the water to flow from the oxidation pond into the stilling area and over the 4 ft baffle and down to the effluent pipe. The baffles will retain all heavy solids while allowing the microbes to be transferred to the second cell. A vertical sampling pipe should be located near the top edge of the dike so that a sample bottle can be lowered to obtain samples of the material flowing between the two ponds.

Oxygen Requirements: With separation of the settleable solids the oxygen requirement will be 0.8 lb/lb BOD.
Daily oxygen demand = 0.8(1670) = 1340 lbs/day.
= 160 mg/l/day

Algae Producton: 1.5 lb oxygen produced/lb of VSS of algae mass produced
Required algae production: 1340/1.5 = 890 lbs/day VSS
Carbon dioxide produced from BOD stabilization = 0.87 (1340)(44/32)
1580 lbs/day
Carbon available from BOD stabilization = (12/44)(1580) = 430 lbs/day
52 mg/l/day
Alkalinity in domestic sewage: 250 mg/l as $CaCO_3$
approximately 300 mg/l as HCO_3
Total carbon in HCO_3 = (12/61)(300)= 59 mg/l
Carbon dioxide in domestic sewage: 50 mg/l at pH 7 and 250 mg/l alkalinity
Carbon in CO_2 = (12/44)(50) = 14 mg/l
Assume raising pH to 8.3 with only the carbon dioxide and the carbon from the BOD stabilization being used.
Carbon used = 52 + 14 = 66 mg/l
Oxygen released by algae synthesis = 1.1 (66)(32/12) = 195 mg/l/day
1620 lbs/day
This is more than adequate oxygen and represents normal levels of operation for domestic sewage oxidation ponds.
Expected algae production: 130 mg/l/day VSS = 1090 lbs/day VSS

Normally, the algae at the surface will raise the pH while the bacteria in the settled sludge will lower the pH. The normal mixing will produce a pH around 8.3 as an average. With shallower ponds the pH will increase and the algae will use some of the alkalinity for their carbon. In deeper ponds the pH will not rise as high. The carbon dioxide-alkalinity-calcium relationships must be carefully evaluated for each design to determine the full extent of algae production.

Effluent quality: BOD = 79 mg/l
Suspended solids = 110 mg/l

Second Cell: Construct the 2nd cell for 20 days retention.
Bottom length = 800 ft.
Top Length = 824 ft.
Surface area = 680,000 sq ft.
= 15.7 acres
Depth = 4 ft.
Effluent pipe is a horizontal pipe set on the floor of the second cell to the third cell without baffles. A sample pipe rises to the top of the dike near the edge to permit sampling of the material moving between ponds.

Effluent quality: The only reaction is endogenous respiration of the algae which will decrease the active mass 20% in 20 days at 20°C. Location of the effluent at the bottom of the pond will permit a further reduction of 25% so that total reduction of algae for each cell after the 1st cell will be 40%.

BOD = 61 mg/l
Suspended solids = 90 mg/l

Series Ponds: In all a total of six ponds with a total of 120 days retention will be required to produce a satisfactory effluent from a BOD and suspended solids standpoint.

Final Effluent Quality: BOD = 8 mg/l
Suspended solids = 11 mg/l
Fecal coliforms - under 200/100 ml

Special Conditions: As the temperature decreases sharply in the Fall of the year, the algae will die and settle. The final effluent will be very good during this period. The algae will return rapidly in Cell 1 since the environment is more conducive to growth. The algae will return more slowly in the 5 remaining cells. When the ponds freeze, algae action will be limited and the good quality effluent will be displaced slowly by the incoming sewage. The retention period should be long enough that the effluent quality will remain satisfactory until the spring thaw and the algae explode in all ponds. The quality of th effluent at this time will depend upon the efficiency of the algae to congregate at the surface. For a few weeks the effluent may not meet the 20-20 requirements; but this generally will occur during periods of spring thaw and rapid runoff permitting a greater discharge without problemsinn the receiving stream. In dry areas the rate of evaporation will exceed the inflow and no discharge will result. In these areas the pond design must be adjusted accordingly.

(b) With Mechanical Equipment

The first cell can be designed the same as without mechanical equipment. The first cell will function normally during the summer period but will have problems when the algae die off in the fall and when ice covers the pond. The aeration equipment should probably be diffused aeration with plastic tubing diffusers placed over the entire area of the pond at mid-depth to prevent disturbing the settled solids and to prevent clogging during the non-winter period. The aeration equipment must be able to transfer all of the required oxygen for bacterial metabolism without assistance from the algae. When the ice melts the aeration equipment should continue to be run until the algae have grown enough to produce the oxygen. Normally, this will take one or two weeks after the ice melts.

Aeration Equipment: Diffused aeration as recommended by manufacturer.
Oxygen transfer = 1340 lbs/day
= 160 mg/l/day
= 6.7 mg/l/hr

Effluent Quality: The effluent will be high in algae and bacteria and will need further treatment prior to discharge.

Second Cell: The second cell should have 20 days retention also and be similar in shape as the second cell in the previous design with a 4 ft. depth and 17.5 acre surface. In order to remove the algae as quickly as possible, 7 baffles are run across the second cell to divide the cell into 8 sections approximately 100 ft wide. A single hole, 12 inches in diameter shall be located at alternating ends of the baffles at the bottom to create 8 subcells operating in a definite flow through pattern to minimize short circuiting. The baffles are designed to minimize mixing and maximize retention of the algae.

Final Subcell: The final subcell is modified to have a 24 inch diameter pipe laid along the bottom of the pond next to the baffle for the full 800 ft. length. A continuously operating chlorinator will add 20 to 24 mg/l chlorine at the entrance to this pipe for disinfection and destruction of the residual algae. The 800 ft. length will give almost 30 minutes contact time prior to discharge into the final subcell with a 2.5 day retention peirod. A series of 7 cross baffles will further divide this last subcell into 8 chambers for the dead algae to settle out. It is expected that the final effluent should meet the required effluent quality at all times. The mechanical aerators, the baffle walls, and the chlorinator are relatively simple changes to replace the four large cells.

Research Needs: There is a need to demonstrate the design criteria proposed in this evaluation study. the proposed design criteria represent The best concepts available at the present time but they have not been studied thoroughly in a single system. It is equally important to demonstrate modification of existing oxidation ponds to obtain high quality effluents.

Specifically, studies should be carried out in the field to demonstrate the value of a submerged rock filter in removing algae from the treated effluent. Laboratory studies have demonstrated that rock filters could assist in the removal of algae which are kept in suspension by wind action. Other forms of algae filters with minimum operational requirements should also be evaluated when available. The key to a quality effluent lies in removal of the algae.

Additional research is needed on the

conversion of large oxidation ponds into multicell ponds to demonstrate the value of multicell units as a means of reducing the algae. Care should be given to the design of the outlet structure from each pond to minimize suspension of the algae.

It appears that chlorination can be used to kill algae as well as bacteria. In fact, disinfection with chlorine results in destruction of the algae more easily than the bacteria. Studies should be made on the construction of a chlorination chamber ahead of a short term sedimentation pond to permit the dead algae to settle out. Surface baffles will be needed in areas having surface winds if mixing is to be prevented.

Since chlorine reacts more readily with the organic matter in algae to form chlorinated hydrocarbons than to completely oxidize the organic matter, research should be carried out as the impact of these chlorinated organics on higher forms of aquatic life which might feed on the chlorinated algae in the receiving stream. Basic studies should be carried out on the identification of the chlorinated organic compounds in view of the persistence and the potential hazards created by the uncontrolled discharge of chlorinated organics into the environment.

Fundamental studies on the growth of algae in domestic sewage would assist in understanding the basic problems in the microbiology of oxidation ponds. Such studies would include the effect of endogenous respiration on the synthesis of new algae and key nutrient elements affecting algae growth.

Studies should be made to demonstrate proper evaluation of pond effluent quality to pond influent loading. The day to day efficiency based on influent and effluent for that day is not a valid method for evaluating oxidation pond efficiency. There is a need to develop a sound evaluation procedure so that engineers can anticipate the effluent quality to be produced from a given set of loading conditions.

Oxidation pond research needs to be oriented to field installations. The laboratory studies in the past have contributed significantly to a general understanding of oxidation pond reactions but have not fully demonstrated the results obtained in the field. It should be recognized that significant field data will take considerable time. Approximately one year of continuous sampling and analysis will be required to obtain a base set of data to evaluate new concepts. A second year of continuous sampling and analysis will be required to examine any one plant modification. By comparison with other forms of biotreatment research on oxidation ponds is slow and difficult. It is important to realize that research results cannot be obtained quickly without increasing the chances of significant error. The size of the ponds are also important in view of the importance of wind mixing.

Oxidation ponds have been a valuable part of the biotreatment complex. The simplicity and the low cost of oxidation ponds have made them attractive for small communities. Unfortunately, these same characteristics which made oxidation ponds attractive to small communities have restricted research and have limited operational data. The net result is a serious gap in adequate information concerning existing oxidation ponds. Since oxidation ponds will continue to have use in the future, it is important that efforts are directed to obtain the necessary data to permit improvement of effluent quality at minimum cost. This is the challenge for research on oxidation ponds.

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SECTION V

AERATED LAGOONS

As the need for improved waste treatment became a necessity, engineers began to look to new treatment concepts. There was a need for a treatment process which produced an intermediate level of treatment between primary treatment and conventional secondary treatment. Industry provided the incentive for development of the aerated lagoon. During the past decade aerated lagoons have found extensive use in both industrial waste treatment and municipal waste treatment.

INITIAL STUDIES

In 1957 (1) the Glatfelder Company of Spring Grove, Pa., began carrying out studies on biological treatment of the process wastes from the manufacture of paper. Initially, a large scale activated sludge system was constructed to study the effect of conventional activated sludge as well as contact stabilization activated sludge. It was estimated that 72% BOD reduction was required at a waste flow of 10 MGD and 78% BOD reduction at 20 MGD. The pilot study showed that activated sludge would treat the waste satisfactorily but the cost was quite high.

Fundamental concepts developed by Weston and Stack (2) indicated that an aeration only system could produce a satisfactory effluent. It was believed that several ponds in series would produce as high a degree of treatment. In order to test the aerated lagoon concept, laboratory units were set up on a batch basis. The results indicated 76% BOD reduction with 2.5 days aeration for a waste with 225 mg/l BOD. Because of the good results, a large scale pilot plant was constructed with a capacity of 98,900 gallons. Diffused aeration was used in this pilot unit. Tests were carried out with 3 and 4 days aeration. The BOD reduction was 55% at 3 days and 68% at 4 days.

It was decided to construct a large scale treatment plant to treat 2.5 MGD of wastes. The treatment plant was constructed with two aeration cells, 110 ft. wide, 12 ft. deep and 703 ft. long. The size of the aeration cells required a different type of aeration system than the diffused aeration system used in the pilot plant. Infilco helped develop a turbine type surface aerator. Mechanical aeration equipment had little use in the United States prior to this time. Three 60 HP Vortair, turbine aerators were placed in each aerator. The cost of the treatment plant was $480,000. Unfortunately, the treatment facility was placed into operation in

January, 1959. January is a bad time to start a biological treatment plant because of the low temperature. It was found that the treatability of the wastewaters had changed. More importantly, it was observed that two ponds in series did not remove the same percentage of BOD as anticipated. The second pond removed much less BOD than the first pond. Thus, it was demonstrated that series ponds could not produce the BOD reduction expected from theoretical analyses of biological treatment. Few people have recognized the importance of this field scale study. It demonstrated that the subsequent ponds were not functioning at the same rate as the first pond. Strangely, this fact has been ignored in the fundamental, mathematical analyses made after this study.

Cost data indicated that aerated lagoons were more expensive than activated sludge. Contract stabilization proved to be the most economical form of biological waste treatment. In March, 1961 the full scale contact stabilization plant got underway.

Aerated lagoons looked like an easy solution to industrial waste problems. Eckenfelder and O'Conner (3) applied the aerated lagoon concept to cannery wastes. They applied the fundamental concepts of biological waste treatmemt to aerated lagoon design. Unfortunately, the mathematics were for a completely mixed system. Their laboratory models were completely mixed but their field scale systems were not completely mixed. The mathematics were not directed towards real system but no one really recognized this essential fact. It suffices to say, the idea worked.

Eckenfelder (4) saw the aerated lagoon as a modification of the activated sludge process. The oxygen requirements ranged from 0.9 to 1.2 lbs O_2/lb. 5 day BOD. Approximately 25% of the oxygen transfer was through the surface. The aerator transferred 2.5 to 3.5 lbs O_2/HP-hr. with 4-7 days aeration. The cost of the aerated lagoon was only 2/3 the cost of a conventional activated sludge system. The problem with the aerated lagoon was the high loss of suspended solids.

Aerated lagoons were connected to industrial wastes until September 1960 when a special study was begun on the treatment of domestic sewage. This study was the result of the imagination and the engineering concepts of Ansel Mitchell and Les Webb. Les Webb believed that aerated lagoons had a broader application than for industrial wastes only. Ansel Mitchell agreed with this basic concept and designed the first aerated lagoon to treat domestic sewage. The University of Kansas was asked to test this unit. McKinney and Edde (5) carried out extensive studies on the 65 ft. diameter aerated lagoon which was aerated with a 3 HP Vortair mechanical aerator. It was found that 76% BOD reduction occurred with 6.4 days aeration. Removal of the suspended solids produced 92% BOD reduction. The aerator transferred 2.0 lbs O_2 HP/hr at 1.0 mg/l D.O.. This study demonstrated that the aerated lagoon was a new concept for domestic sewage as well.

Aerated lagoons were suddenly a major factor in wastewater treatment. Overloaded oxidation ponds plus the need for partial treatment stimulated application of aerated lagoons. Examination of fundamentals (5a) showed that temperature, mixing, O_2 transfer, retention time, and microbes were all important factors in BOD reduction. It was observed that few aerated lagoons were truly completely mixed systems. The problem was a lack of adequate mixing. Aerated lagoons were affected primarily by oxygen transfer and mixing. The initial studies indicate that mechanical aeration equipment could transfer 1.5 lbs O_2 HP.hr.. With 24 hours aeration 50% BOD removal was expected. For the first time the engineer was furnished with design data for aerated lagoon to treat either domestic sewage or industrial wastes.

Red Bridge furnished a fruitful area for research. A second aerated lagoon was designed to demonstrate the feasibility of the aerobic-anaerobic concept. A 10 ft. deep aerated lagoon was constructed in hopes that the bottom 5 ft. would be anaerobic while the upper 5 ft. would be aerobic. The hydraulic mixing concepts changed the operational characteristics of the system. The entire area around the mechanical mixer remained aerobic while the area further out was anaerobic. Evaluation of both aerated lagoon systems (6) showed 1.8 lbs O_2 HP. hr. Mixing was a problem for both units. It was felt that 1/5 to 1/4 HP was required/100 cf of aeration volume. Adequate power was needed to keep the solids in suspension. The BOD reduction was 63% for 1.7 days aeration and 78% for 7.1 days aeration. The primary cause of the residual BOD was unflocculated microbial solids. Placing an oxidation pond following the aerated lagoon resulted in removal of the suspended solids but permitted algae to grow up. Operational data showed that the effluent BOD from the oxidation pond was essentially the same before and after construction of the aerated lagoon. The effluent BOD was created by algae and averaged 30 mg/l.

Mancini and Barnhart (7) applied fundamental concepts to the design of aerated lagoons for industrial wastes. Their equations were developed for complete mixing systems. Sawyer (8) felt that aerated lagoons should be operated as complete mixing systems. He preferred mechanical surface aeration over diffused aeration because of mixing and power requirements. Aerated lagoons produced 0.5 pounds suspended solids per pound of BOD stabilized and requires from 0.8 to 1.2 pounds of oxygen per pound of BOD. Caution was urged for aerators over 25 HP as there was a tendency to create too much localized mixing and not enough mixing for the entire tank.

The conversion of overloaded oxidation ponds to aerated lagoons became a standard practice for increasing the load on ponds. Typical was the conversion of the oxidation ponds at Travis Air Force Base (9). Laboratory studies showed that sedimentation ponds following the aerated lagoons would produce an effluent of 10 mg/l BOD. The aerated lagoons for 2 MGD of wastes were designed with 9-15 HP mechanical aerators spaced 70 ft. apart.

Aerated lagoons have also been used for tertiary treatment (10). Peak flow periods caused loss of solids from a contact stabilization activated sludge plant in East Windsor, New Jersey. A 3.11 acre aerated lagoon using diffused aeration was placed in operation after the activated sludge plant. The influent BOD and SS was 80 mg/l at peak flows. The effluent BOD and SS were from 12-15 mg/l.

Examination of 10 years experience with aerated lagoons by Benjes (11) indicated that there were three basic types of aerated lagoons: 1. the complete mixing aerated lagoon where all contents of the aeration cell were held in suspension; 2. facultative aerated lagoons where some solids settle out due to incomplete mixing; and 3. aerated oxidation ponds where there is little mixing. Examination of theoretical design equations by Eckenfelder, McKinney and Monod revealed slight differences in approach but no serious differences. Mixing and aeration was of primary concern. Turbine type aerators were more efficient than propeller type aerators as far as pumping fluid was concerned. It was indicated that pumpage was only 2,000 gpm/HP and oxygen transfer was 2 pounds oxygen/HP/hr. When aerated lagoons have less than 24 hours retention the power for oxygen transfer controls the design. Above 24 hours retention the power for mixing controls.

A simplified kinetic theory for aerated lagoon design was developed by Marais and Capri (12). It was felt that several ponds in series could achieve more efficient BOD reduction than one single pond. The key lay in the fact that metabolism progressed at the same rate in all ponds. Unfortunately, the earlier studies of Rice and Weston (1) had shown that the kinetic rate of metabolism was not the same in all series ponds. Basically, metabolism will convert all the organics of microbes in the first pond provided there is adequate mixing and oxygen. The other ponds will primarily be concerned with stabilization of cells. This points to the need to combine mathematical concepts with biological concepts to develop sound design criteria.

INDUSTRIAL WASTES

Industry provided the initial impetus for the development of aerated lagoons and furnished much of the early design and operational information.

Pulp and Paper:

The pulp and paper industry has found extensive use for aerated lagoons. Eckenfelder (13) examined the need for additional nutrients such as nitrogen and phosphorus for treating pulp and paper wastewaters. He showed that the prime problem with the lack of nitrients was a slower rate of BOD removal. Basically, nutrients are exchangeable with aeration time provided there is at least a minimum level of nitrients in the wastewater.

Gehm (14) felt that aerated lagoons did not offer any advantages over activated sludge and could not produce as good an effluent. It was felt that a high degree of treatment was needed for pulp and paper wastes and it could not be provided for by aerated lagoons.

Yet, there was a need to build wastewater treatment plants as economical as possible. The aerated lagoon offered an economical method for meeting the needs of a number of pulp and paper plants. Weyerhaeuser Company (15) built aerated lagoon systems at its Springfield, Oregon, and Cosmopolis, Washington plants. The Springfield aerated lagoon covered 21 acres with a depth of 10 ft. The wastewaters and an 8 day detention time with an influent BOD of 200 mg/l and an effluent BOD of 16 mg/l. Aeration was designed to transfer 20,000 pounds of oxygen a day with 5-75 Yeoman surface aerators with a 20 HP Infilco aerator as a spare. The Cosmopolis aerated lagoon system consisted of two parallel lagoons each with 5.5 million gallons capacity and 8-75 Yeoman aerators. The retention period was 5 days. The avearge BOD of the wastewaters was 4,000 mg/l. BOD reductions from 83 to 95% were achieved. The Kamloops Pulp and Paper Company in Kamloops, British Columbia, had 23 acres of aerated lagoons, 10 to 12 feet deep. The retention period was 7 days at 13 MGD flow. There were 4-60 HP fixed aerators and 5-15 HP floating aerators. One of problems was icing of the aerators during the winter. Low temperatures definitely reduced BOD reduction. Fortunately, the raw wastes were able to keep the temperature around 60°F.

The Packaging Corporation of America plant at Rittman, Ohio (16) had a waste flow of 3 MGD. Primary treatment removed 90% suspended solids and 25% BOD. The settled effluent was treated in four earthen aerated lagoons. Two units were 200 ft. by 500 ft. with 8 ft. depth. There were 3-30 HP aerators in each of these lagoons. The other two units were 240 ft. by 310 ft. with 8 ft. depth. The units had 3-40 HP aerators. After 11 days aeration the effluent had 69 mg/l BOD. A 7 day sedimentation period after aeration only lowered the BOD to 63 mg/l. Post aeration with a 20 HP floating Aqualator in an 80,000 gallon basin raised the effluent D.O. to 3.8 mg/l with a BOD of 56 mg/l. The treatment operations cost $0.64/MG. The primary operational problem was the gear boxes on the aerators. Overall the BOD reduction was 86%.

The Riegel Paper Company plant (17) in Riegelwood, North Carolina had 230 acres of ponds to handle the wastes from 200 tons of bleached kraft pulp per day. Originally, 14-60 HP floating aerators were added to the ponds. It was anticipated that the aerators would transfer 3.3 pounds oxygen/ HP/hour. It was necessary to operate the aerators only in the summer. The aerators cost $155,000 with a power cost of $40,000/year. The current BOD load was 108,000 pounds per day with an effluent of 18,000 pounds per day. An additional 15-20 HP aerators were added to give additional oxygen.

The Moraine Division plant of Kimberly Clark at West Carrollton, Ohio (18) produces 5.5 MGD. The heavy suspended solids load required primary sedimentation prior to the aerated lagoons. Two aerated lagoons were employed 1400 ft. long by 145 ft. wide and 14 ft. deep. The aeration capacity gave a 6 day retention with 3-60 HP floating aerators in each cell. The influent BOD to the aerated lagoon was 375 mg/l and the effluent BOD was 50 mg/l. The change in suspended solids was from 100 mg/l to 60 mg/l. The major operating problem was ice on the aerators.

Summarizing industry activity, Gellman and Berger (19) reported that there were 11 installations treating 150 MGD. By and large evaluation of aerated lagoons in the pulp and paper industry was with equations presented either by Eckenfelder or McKinney. It was apparent that aerated lagoons were of major importance to the pulp and paper industry.

Textile:

Cotton textile wastes pose problems similar to pulp and paper wastes. They are generally high in carbohydrates and low in nutrients. In addition the pH is generally high, above 9.5. Studies at Mooresville Mills in Mooresville, North Carolina (20) indicated that aerated lagoons could be used to treat cotton textile wastes. Two concrete tanks, 254 ft. long, 112 ft. wide and 12 ft. deep, were constructed to give a 48 hour aeration to a flow of 2 MGD. Four 25 HP mechanical aerators were selected for aeration. The aerated lagoon was followed by a settling lagoon 122 ft. long, 68 ft. wide, and 12 ft. deep. The sedimentation time was 12 hours at average flow. The estimated construction cost was $234,000 with $7,400/year in operation costs.

Dye wastes present a problem of color in addition to the soluble organics. The wastewaters from the United Piece Dye Works in Bluefield, Virginia, (21) had a pH of 6.8, 85 mg/l SS, 325 mg/l BOD, and 750 mg/l COD. Chemical treatment was necessary to remove the color. Lime plus an anionic polyelectrolyte was used to flocculate the wastes prior to neutralization and biotreatment. The aerated lagoon system consisted of four lagoons in series with a total of 5 days retention. The first lagoon had 100 HP mechanical aeration with 2 days retention. The second lagoon had a 20HP floating Aqualator. The third lagoon had 2-20 HP Aqualators and the fourth lagoon had a 20 HP Aqualator. During summer months the system gave 90% BOD reduction with 20 mg/l BOD in the effluent. The BOD reduction in the winter was only 50% with an effluent having 160 mg/l BOD.

Refinery:

Oxidation ponds have had extensive use in treating process wastes from refineries. It was only natural that aerated lagoons would be used where land was limited or to increase the capacity of existing systems. The American Oil Company refinery located at Sugar Creek, Missouri, was faced with limited land for waste treatment facilities and constructed a four cell treatment system. The first cell was designed as an oil skimming unit. The next two cells were aerated lagoons. The final cell was a sedimentation cell. The first aerated lagoon was 120 ft. by 713 ft. by 10 ft. with 3-60 HP Vortair mechanical aerators. The second lagoon was the same size but contained only 3-15 HP Vortair mechanical aeration. Two studies on this system (22)(23) at a flow of 8 MGD showed 89% reduction in oil; 197 mg/l to 22 mg/l; 94% reduction in phenol, 7.4 mg/l to 0.4 mg/l; 69% reduction in COD 467 mg/l to 146 mg/l; and 76% BOD reduction, 175 mg/l to 42 mg/l. It was apparent from the results that oxygen transfer was limiting the treatment efficiency. The oxygen demand at the first aerator demonstrated the hydraulic effect of a plug flow type aerator. Additional floating aerators have since been added to try to meet the oxygen demand.

The Humble Oil and Refining Company plant at Houston, Texas (24) had a dry weather flow of 15 to 18 MGD. The wastewaters have 975 mg/l COD, 227 mg/l BOD, 54 mg/l NH_3-N, and 2.5 mg/l PO_4. The aerated lagoon covered 7.75 acres with 16-60 HP mechanical aerators at 80-150 ft. spacings. Unfortunately, the data indicated a lack of sufficient mixing and dissolved oxygen for good treatment. This illustrates one of the major problems facing aerated lagoons, too much volume of lagoon and not enough mixing.

Chemical:

Chemical wastes are similar to refinery wastes being primarily soluble hydrocarbons. The 3M Company wastes (25) had 237 mg/l BOD, 15 mg/l phenol, and a pH of 6.1. An aerated lagoon 47 ft. by 26 ft by 5 ft., 38,000 gallons, was constructed to treat these wastes. With 4.6 days retention at 71°F the unit showed 90% BOD reduction. At 51°F the BOD reduction dropped to 25%. This illustrates the impact of temperature on aerated lagoons. Tests on phenol removal showed that phenol and BOD removal followed the same pattern, indicating that phenol was easily removed by microorganisms.

One of the largest aerated lagoons for synthetic chemicals was constructed by Union Carbide (26) to treat 50,000 lbs BOD/day. The aerated lagoon facility cost $900,000 and was designed to treat 5.3 MGD wastes having a BOD of 2,100 mg/l. An initial laboratory study showed 98-94% BOD reduction with 5 to 15 days aeration at 23°C. At 9°C the BOD reduction was 83-87% with 5-8 days aeration and 63-71% with 2.5-5 days aeration. The treatment system had 66 hours aeration and 4 hours sedimentation. Operational data during the summer showed 35°C, 0 mg/l D.O., 54% BOD removal at 46 lbs BOD/1000 cf/day with 2.9 days aeration time. Winter operations with 2.3 days aeration time and 15°C showed 2.0 mg/l D.O. at 56 lbs BOD/1000 cf/day and 40% BOD removal. The oxygen transfer characteristics of the Yeoman type mechanical aerators were measured at 2.68 lbs O_2/HP/hr at 20°C and zero D.O. The BOD removal rates were 25 lbs/1000 cf/day at 24-36°C and 27 lbs/1000 cf/day at 15°C. The microbial cells resulting from metabolism were quite dispersed and did not settle in the sedimentation pond. This system was limited by oxygen transfer characteristics as were many aerated lagoon systems, especially large systems.

Roofing:

A small asphalt roofing shingle manufacturer utilized waste paper and rags for roofing felt. The Tamko Asphalt Products Plant (27) in Joplin, Missouri, produced 150,000 gpd wastes 7 days a week. The wastes were discharged to a series of ponds but the ponds were full of solids. It was decided to use aerated lagoons as pretreatment prior to discharge to the municipal sewerage system. The aerated lagoon system consisted of an equalization basin with 1.4 days retention, an aerated lagoon with 0.9 days retention, and polishing ponds with 3.6 days retention. The operating data showed the raw wastes had a BOD of 975 mg/l. The influent to the aerated lagoon had 900 mg/l BOD and the effluent had 340 mg/l. The polishing ponds reduced the BOD to 275 mg/l prior to discharge to the sanitary sewer. The suspended solids were reduced from 990 mg/l to 145 mg/l. The basic metabolic reaction was limited by oxygen transfer as only one of the three mechanical aerators was initially placed in service. In spite of the oxygen deficiency, the system met the performance requirements for discharge to the sanitary sewer.

Food Processing:

Food processing plants produce strong wastes that are largely soluble or colloidal. The initial use of oxidation ponds for food processing wastes led to overloaded conditions and the need for aeration. Typical of this problem was the Sandwich West Township (28) that had a dairy supplying 80% of the flow. A 2 1/2 day aerated lagoon was constructed ahead of a 3 month retention oxidation pond. The aerated lagoon was 8 feet deep with 221,000 Imp. gallons capacity and had a 20 HP Simcar mechanical aerator. The oxidation pond had a 4 ft depth and a surface area of 6.8 acres. The influent BOD was 370 lbs/day, and the effluent BOD was 253 lbs/day. The oxygen uptake rate was 5.7 mg/l hour. The high pH of the wastes, 9-10, appeared to retard biological activity in the aerated lagoon.

Park River, North Dakota, (29) had a small potato flake plant which discharged its wastes to the sanitary sewer. In order to provide additional treatment, a single cell aerated lagoon one acre in size, 8 ft. deep, was constructed. The retention period was 6-14 days during maximum load. A single 25 HP Vortair aerator was used to provide proper oxygen transfer. It was found that 90% BOD reduction could be obtained at a loading of 300 lbs BOD/acre/day.

Potato processing wastes in Idaho were studied quite extensively (30) over a two year period in 3 pilot lagoons. One system employed an aerated lagoon following primary sedimentation while the other system used one lagoon as an anaerobic lagoon followed by an aerated lagoon. The test ponds were 40 ft. square and 10 ft. deep. The aerated lagoon following primary sedimentation had a 10 HP Eimco surface aerator while the aerated lagoon after the anaerobic lagoon had a 5 HP Welles floating aerator. The aerated lagoon only showed 55% BOD reduction at 24 lbs BOD/1000 cf/day with 4.2 days retention. The BOD reduction increased to 81% at 11.3 lbs BOD/1000 cf/day and 7.8 days aeration. The aerated lagoon following the anaerobic lagoon showed 83% BOD reduction at 20 lbs BOD/1000 cf/day. Increasing the load to 44 lbs BOD/ 1000 cf/day reduced the BOD removal to 50% oxygen transfer was the limiting factor in treatment efficiency.

Pea processing wastes at Ferndale, Washington, (31), were treated in a 1.75 acre aerated lagoon, 10 ft deep. The aeration equipment consisted of four 50 HP surface aerators. The effluent from the aerated lagoon went to a 135,000 gallon polishing pond. During pea processing 96,000 to 180,000 lbs of peas were processed with 3,500 gallons of wastes produced per 1000 pounds of peas processed. The influent BOD averaged 820 mg/l. The aerated lagoon effluent had 196 mg/l BOD and the final effluent had 182 mg/l BOD. The soluble BOD was only 35 mg/l. Microscopic examination of the activated sludge showed predomination of Sphaerotilus and flaggellated protozoa. The high BOD load created less than optimum conditions.

Fruit processing wastes at Yakima, Washington were treated in a 6 MG aerated lagoon, 280 ft. square and 12.5 ft. depth. Four 60 HP surface aerators were used to treat 20,000 BOD/day in 1967. The aerated lagoon gave 70% BOD removal but produced excessive quantities of suspended solids. In 1968 a 150 HP surface aerator was added as was a 90 ft diameter final clarifier. The complete mixing concept provided adequate treatment as long as nutrients are added. The mechanical aerator provided 0.3 HP/1000 cf for mixing and 2 lbs O_2/ HP-hour. Material balances indicated that 0.46 lbs O_2 were used for each pound of BOD removed. Destruction of volatile suspended solids required 1.2 pounds of oxygen per pound of VSS destroyed. The cost of treatment was $0.041/pound BOD removed. (32).

Mink food manufacturing at Midvale, Utah, resulted in wastes that were treated in two aerated lagoons operating in series. The aeration equipment consisted of a 10 HP 146 SCFM air blower to 5,000 ft of aeration tubing in the primary lagoon and 2,500 ft. of aeration tubing in the secondary lagoon. The retention time was 30 days with 90% BOD reduction. The secondary lagoon showed very profuse algae growth. The aeration tubing tended to clog but were cleaned by the use of HCL gas. Approximately 20 minutes cleaning time was required at a cost of under $20/month. (33).

Packinghouse and Animal Wastes:

As the aerated lagoon began to show promise as a simple system for treating wastewaters, it was only natural to try aerated lagoons for animal wastes. Unfortunately, animal wastes are very concentrated and are not easily treated aerobically. Two schemes were developed for treating animal wastes. One scheme employed anaerobic lagoons ahead of the aerated lagoons and the other scheme employed dilution with treated wastes.

Research at the University of Kansas during the early part of the 1960 decade, resulted in a demonstration project employing the anaerobic-aerated lagoon concept for cattle manure (34). This project operated over a 3 year period from 1966 to 1969 and demonstrated the problems of this system for treating manure from a beef cattle feedlot. At the same time parallel studies were being carried out on aerobic treatment of hog manure in confined buildings. In January, 1966, the first full scale aerated lagoon for hog manure treatment within a building was placed into operation near Lawrence, Kansas. A study (35) by the University of Kansas demonstrated that the self contained, aerated lagoon could readily convert, odorous hog manure into microbial solids which were easily applied to agricultural lands.

The University of Illinois also carried out tests (36) on aerated lagoon treatment of hog manure in confined buildings. The BOD of the hog manure was reduced from 35,000 mg/l to approximately 3,000 mg/l. The retention period of the manure in the aerated lagoon was approximately 50 days. By 1969 there were over 100 confined hog manure aerated lagoons in operation.

Studies on dairy cattle manure treatment in a conventional aerated lagoon employing a floating, mechanical aerator (37) found that 0.10 HP was needed per cow as well as 1400 cu. ft. of lagoon volume per cow. Hart (38) felt aerated lagoons left a lot to be desired when applied to animal manures. The effluent from aerated lagoons treating animal manure cannot be discharged directly to streams as they contain too much salt and suspended solids. Improper applications have produced poor systems that failed to work properly. Yet, it should be recognized that many systems are working properly.

The treatment of slaughter house wastes from Farmbest in Iowa Falls, Iowa, utilizes anaerobic-aerated lagoons in series. The aerated lagoons consist of two cells in series after the anaerobic lagoons with 40 days detention. Aeration was supplied by a diffused aeration system employing 52,000 ft. of plastic tubing. Three 595 cfm compressors at 9 psi are available for aeration. The first lagoon gave 92% BOD removal and 79% suspended solids reduction. The second lagoon gave 45% BOD removal and 50% suspended solids reduction. The turbulence created by the diffused aeration system was adequate to mix the wastes but were not adequate to keep the suspended solids in suspension. The final effluent contained 30 mg/l BOD and 48 mg/l suspended solids for 95% treatment.

The Sterling Processing Company in Oakland, Maryland, employs two aerated lagoons in series to handle poultry processing wastes (40). The first pond is 590 ft. long, 140 ft wide, and 6 ft. deep while the second pond is 230 ft. long, 140 ft. wide and 6 ft. deep. Diffused aeration is supplied through 104 Link Belt Aero Circulators at the rate of 2800 cfm. The raw wastes range from 800 to 1000 mg/l BOD. The effluent from the first aerated lagoon has 70-100 mg/l BOD while the final effluent has 30 mg/l BOD. The total aeration time is 14 days.

It can be seen that aerated lagoons have had extensive use in treating industrial wastes. Much has been learned from these industrial applications because they have covered a wide range of loading conditions and have employed several different design concepts. One of the important parts of aerated lagoons is the aeration equipment. Both mechanical aerators and diffused aeration have been employed in aerated lagoons.

AERATION EQUIPMENT

MECHANICAL AERATION:

Mechanical aeration has been used in activated sludge systems since 1920 but little scientific progress was made on mechanical aeration in the United States prior to their use in the Glatfelder aerated lagoon. Weston and Stack (41) studied the surface, turbine type aerator using sodium sulfite in tap water. The sodium sulfite removed the oxygen from the water and permitted determination of the rate of reaeration. They found that the mechanical aerator could transfer from 3 to 4 pounds of oxygen per HP-hour.

Examination of mechanical aerators by Eckenfelder (42) indicated that 10 to 20% of the oxygen transfer was due to surface aeration and the rest was caused by the mechanical device proper. Mechanical aerators were found to transfer 4.0 to 4.5 lbs O_2/HP-hr at 0 mg/l D.O. and 20°C. Eckenfelder designed a basic equation to permit translation of data from one set of conditions to another set.

$$N = N_o \frac{C_{sw}-C_L}{C_s} .1.02^{(t-20)} . \alpha$$

where N_o = lbs O_2 transferred/HP-hr in water at 20°C and 0 mg/l D.O.

N = lbs O_2 transferred/HP-hr in lagoon under operating conditions

C_{sw} = O_2 saturation in lagoon, mg/l

C_L = O_2 in lagoon, mg/l

C_s = O_2 saturation in water at 20°C, mg/l

t = lagoon temperature, °C

α = O_2 transfer ratio of waste to water

One important observation was that tank geometry was significant in selecting the number of aerators. Unfortunately, no insight was given on the effect tank geometry had on aeration selection.

Weston (43)(44) made a careful evaluation of the Infilco Vortair aerator. He found that the turbine type aerator created a hydraulic jump with air being pulled in behind the blades. The turbine then shears the air into tiny bubbles. As the turbine speeds up, the blades overlapped and reduced oxygen transfer. Power requirements for turbine type aerators were related to power number and submergence, permitting proper design of turbine size, speed and power. It was found that this type of aerator transferred 3.7 lbs O_2/HP-hr. at low speeds and 3.1 lbs O_2/HP-hr at high speeds.

Evaluation of surface aerators by McWhirter (45) indicated good mixing was not easily achieved. This resulted in variations in K_La at different points in the aeration tank. Lightnin mixer produced uniform mixing and oxygen transfer.

Paddle wheel mechanical aerators were almost as old as activated sludge. The Haworth paddles at Sheffield, England, were the first mechanical aerators; but it was the Kessener brush in Holland in 1926 that was the first, high velocity brush type aerator. Eventually, the cage rotor replaced the brush aerator. One of the first studies in the United States on cage rotors was at Iowa State University (46). The cage rotor was 27 1/2" diameter, 3 ft. long, and driven with a 10 HP motor. The data collected by Knight indicated 5.65 lbs O_2 transfer/ft. of rotor length at 12 inches submergence and 100 RPM. He, too, felt that oxygen transfer was affected by water volume and geometry of tank. Studies of one tank could not be applied to another tank.

Baumann and Cleasby followed up with Knights data in a relatively small test tank (47). They found that the cage rotor transferred different rates of oxygen at different submergences and different speeds of rotation. One of the problems in evaluating mechanical aerators was in the relationships between water power requirements and wire power requirements. The waterpower requirements measure the theoretical power required while the wire power measures the paid-for-power. Frankly, only the latter really counts. It was found that motor and gear reducer losses accounted for a 25% loss in power through the system.

Few consulting engineers were concerned about mechanical aeration in 1965, much less the cage rotor. Kalinske (48) recognized that oxygen transfer with mechanical aerators was related primarily to the water pumped through the aerator.

$$Q_o = Q_w(C_2 - C_1)$$

where Q_o = lbs O_2/time

Q_w = lbs water flow/time

C_2 = O_2 conc. at outflow, mg/l

C_1 = O_2 conc. at inflow, mg/l

There was also a factor related to oxygen transfer per pass through the aerator. Kalinske rated K_La to pumped flow, the transfer factor, and tank volume.

$$K_La = \frac{Q_wK}{w}$$

where K = the oxygen transfer efficiency per pass

w = tank water mass, lbs.

He felt complete mixing was important to oxygen transfer; but the water pump concept was his most important contribution.

Theoretical concepts were of little value outside of technical meetings. Yet, a few people began to recognize that mechanical aerators would have more widespread use if methods were developed for proper field testing. Union Carbide was faced with the use of aerated lagoons and developed the techniques needed to evaluate the aerators (49). The Institute Plant of Union Carbide consisted of 3-5 MG earthen basins 17 ft. deep with 4-6 75 HP mechanical aerators. The K_La at 20°C was determined to be 1.45/hour. Studies at Rockford, Illinois, with a 450,000 gallon tank, 70 ft. diameter and 17 ft. deep with one 75 HP mechanical aerator gave a K_La of 6.6/hour. It was obvious that many factors affected oxygen transfer but techniques were available to evaluate mechanical aerators.

Eckenfelder and Ford (50)(51) presented an old concept to translate basic oxygen transfer data from one unit to another unit. They felt that 60% of the oxygen was transferrred in the spray and 40% in the turbulence and entrainment. A bottom velocity of 0.4 to 0.5 fps was needed to prevent bottom deposition of solids. It was found that 0.3 HP/1000 cf of aeration volume was required for minimum mixing.

The cage rotor came into its own with its application to confined hog manure treatment. The University of Illinois (52) studied three different types of cage rotors at 100 RPM. The angle iron cage rotor had 1.6 lbs O_2/ft. of rotor. The rectangular plate had 1.7 lbs O_2/ft. The expanded metal rotor had 1.0 lbs O_2/ft. at 2 inches immersion and 1.5 lbs O_2/ft. at 4 inches immersion. It appeared that the rectangular plate rotor was the most efficient aerator of those studied. With increased application of caged rotors to confined animal buildings, it was apparent that more data would be forth coming in the future. One thing for certain, mechanical aeration came into its own with development of the aerated lagoon.

DIFFUSED AERATION:

Oxidation ponds worked well for domestic sewage as long as they were not loaded excessively. Diffused aeration equipment was added to oxidation ponds in an effort to increase the oxygen transfer. In order to distribute the oxygen over the entire oxidation pond, plastic tubing with tiny slits was sunk to the bottom of the pond. Diffused air was blown through the complex distribution system to give broad aeration. One of the first installations was in Tinley Heights near Chicago (53). A 0.9 acre pond, 4.5 ft. deep was designed for a BOD load of 30 lbs/acre/day but was soon overloaded. In 1961 2500 ft. of plastic tubing was added to the pond; and air was supplied by a 5 HP, 54 cfm air compressor operating at 10 psi. One and one-half years data indicated a load of 130 lbs BOD/acre/day. The raw wastes had a BOD of 174 mg/l while the effluent had a BOD of 29 mg/l. The suspended solids changed from 134 mg/l to 54 mg/l. These data show that the BOD in the sewage was converted to suspended solids, not all of which settled in the pond.

The Raytown, Missouri, Southwood oxidation pond (54) was overloaded and expanded by adding mechanical aeration. Continued increases in organic loading resulted in the need for additional oxygen. Approximately 24,000 ft. of plastic tubing was added to a 4.8 acre oxidation pond together with a 30 HP air compressor, 590 cfm at 9 psi. The estimated organic load was 1,000 lbs BOD per day.

Lee's Summit, Missouri, also found itself with an overloaded oxidation pond (55). The Little Cedar Creek oxidation pond was designed for 60,000 ft. of plastic tubing. Initially, 42,000 ft. was installed with two 25 HP air compressors, 1,000 cfm at 9 psi. The oxidation pond covered 25 acres with a depth of 5 feet.

The success of diffused aeration to increase the organic load on oxidation ponds soon led to the design of aerated lagoons employing plastic tubing. Norway, Maine (56) constructed a 10 acre aerated lagoon employing 23,500 ft. of plastic tubing with a 25 HP air compressor, 500 cfm. The BOD load was designed for 600 lbs/day with 90-95% reduction. Sludge accumulation was expected to be only 6 inches in 50 years.

Tertiary treatment began to be a problem in the 1960's. Ponds were placed after primary and secondary treatment plants to produce a higher quality effluent. Mound, Minnesota, and Spring Park, Minnesota employed an aerated lagoon following an activated sludge system (57). The aerated lagoon had a retention peirod of 7.5 days at 1.25 MGD design flow. The BOD load at design flow was only 20 lbs/acre/day but it was the most difficult part of the BOD to remove. A 15 HP air compressor, 215 cfm air, supplied the required air to the plastic tubing. The BOD reduction was 96 to 98%.

Two cell aerated lagoons were designed to produce maximum BOD reduction. The Harvey, North Dakota, STP (58) had two 1 1/2 acre diffused aeration aerated lagoons, with 20 days retention. Air was supplied by two 15 HP air compressors, 270 cfm at 9 psi, through 15,000 ft. of plastic tubing. Only one compressor was used at any one time. The primary cell was loaded at 400 pounds BOD/acre/day while the secondary cell was loaded at 100 pounds BOD/acre/day. The final effluent had a BOD of 22 mg/l.

The largest diffused aeration aerated lagoons were constructed at Regina, Saskatchewan (59). Two 105 acre lagoons were designed to take the overload from a trickling filter plant. The ponds had a 40 day retention with 845,000 ft. of plastic tubing and 30-30 HP air compressors, 595 cfm at 9 psi. The air flow was 0.582 cfm/lb BOD applied. The final effluent

BOD was 20 mg/l, 90% reduction.

McKinney (60) reported on the first detailed study of diffused aeration aerated lagoons. Examination of the aerated lagoons at Lee's Summit, Missouri, and Raytown, Missouri, gave sufficient data to evaluate this treatment system. The Lee's Summit oxidation pond was converted to an aerated lagoon with 30 days retention time. The average BOD of the raw wastes was 125 mg/l while the effulent averaged 26 mg/l. The COD of the influent averaged 360 mg/l and the effluent averaged 156 mg/l. A major fraction of the effluent COD was in suspended solids, which averaged 70 mg/l. The effluent suspended solids were largely algae cells. The low effluent BOD indicated that most of the algae were dead. The primary operating problem was clogging of the plastic tubing aerators with calcium carbonate. Periodic application of hydrochloric acid to the air distribution system was needed to keep the aerators clean. The Raytown, Missouri system employed a mechanical aerated lagoon ahead of 4.8 acre oxidation pond. The oxidation pond was converted to a diffused aeration aerated lagoon by adding 24,000 ft. of plastic tubing and a 30 HP air compressor. The mechanical aerated lagoon employed two 15 HP surface aerators in a 24 hour retention basin. The BOD of the raw sewage was 180 mg/l. The mechanical aerated lagoon reduced the BOD to 80 mg/l while the diffused aeration aerated lagoon reduced the BOD to 30 mg/l. The change in COD was from 460 mg/l to 300 mg/l to 200 mg/l. The final effluent suspended solids averaged 70 mg/l. Both treatment systems were loaded at 10,000 PE and produced essentially the same effluent quality in spite of the fact that the Raytown plant had one-fifth the size of the Lee's Summit plant. These results helped to confirm the fact that the effluent quality from long retention period treatment plants is controlled by the growth and discharge of algae rather than by incomplete treatment of the wastewaters.

The multiple cell diffused aeration aerated lagoon has continued to gain popularity (61-63). The success of the plastic tubing led to the development of other forms of diffused aeration. The air gun was developed to give mixing and aeration in a deep lagoon. Basically, the air gun consists of an air chamber and a long open tube. Air is supplied to the air chamber until a given discharge pressure is reached. The air then discharges to the open tube which becomes an air lift pump. Material is drawn in at the bottom of the tube and discharges at the top like a gun. Fisher (64)(65) reported on the use of an air gun aerated lagoon for treating potato processing wastewaters. The aerated lagoon was 850 ft. long, 280 ft. wide and 9 ft. deep with 127 air guns. Air was supplied by two axial flow air blowers, 40 HP, 780 cfm at 9 psi.

With 16 days aeration time the BOD was reduced from 855 mg/l to 72 mg/l. Two ponds in series after the aerated lagoon reduced the BOD to 29 mg/l.

Another air tube has been developed by Polcon Corporation (66). This air tube employs an internal helix to mix the air with the fluid being aerated. Each helixor aerator uses 22-28 scfm air. At 23 scfm the aerator will transfer 2.7 lbs oxygen/hour to the wastes being treated, according to the manufacturer.

The different forms of aeration equipment for aerated lagoons has led to numerous claims and counter claims. In an effort to determine the best equipment for aerated lagoons, a comparative study was made on three types of aerators at Winnipeg, Canada (67). Three parallel aerated lagoons were constructed to treat 0.5 Imp. MGD. The plastic tubing aerated lagoon had a 30 day retention period using two cells in series with a depth of 10 feet. A 30 HP compressor supplied the air to the plastic tubing. The air gun aerated lagoon had a 20 day retention period with a 17 ft. depth. Air was supplied by 54 air guns with a 40 HP air compressor. The mechanical aeration aerated lagoon used 8-20 HP units in series with 20 days retention and a 11 ft. depth. A study over a 21 month period indicated a raw waste with 175 mg/l BOD and 188 mg/l suspended solids. The plastic tubing unit had an effluent with 37 mg/l BOD, 34 mg/l SS, 12.6% nitrogen reduction, and 23.3% phosphorus removal. The effluent from the mechanical aeration unit had 38 mg/l BOD, 39 mg/l SS, 14.6% nitrogen reduction, and 19.5% phosphorus removal. The data indicated no significant differences in treatment efficiency for these three systems. The major problem in all three units was accumulation of solids in the aerated lagoons. Solids assumulated at the rate of one ton per Imp. MG of wastes treated. Accumulation of this amount of solids was unexpected and no provisions were made for its removal. Other operational problems included clogging of both the plastic tubing and the air gun and ice accumulation on the surface aerator. Cost data for the three systems were as follows:

	Capital Cost	Operating Cost
Plastic tubing	$336,800	$46/Imp MGD
Air gun	301,000	49/Imp MGD
Surface aerator	347,800	100/Imp MGD

It can be seen that diffused aeration was the most economical form of aeration in these systems. Unfortunately, the three aerated lagoons were designed as long term aerated lagoons and werenot necessarily optimum for waste treatment. The net result is that these data can be misleading if care is not taken to properly apply them.

LOW TEMPERATURE

One of the major operational problems with aerated lagoons has been low temperature. Low temperature affects surface aerator by building up ice on the aerator, throwing it out of balance. Low temperature also slows the rate of metabolism. When mixing is not sufficient, solids will settle out and build up in the aeration tank. When the temperature increases, the settled solids will undergo more rapid metabolism and increase the load on the aerators.

Studies in Alaska (68) with a diffused aeration system at the Eielson Air Force Base for domestic sewage showed 66% BOD removal with a 40-50 mg/l effluent. The temperature of the aeration tank contents was 1°C. It appeared that optimum results occurred with a 20 day retention period. This study was later expanded to cover two additional systems (69). BOD reductions up to 87% were achieved in the field. Better treatment results required longer aeration periods.

Canadian research on mechanical surface aerators (70) indicated that icing conditions required mounting the aerators on permanent structures rather than on floats. There was some concern on the value of aerated lagoons at low temperatures. The low rate of metabolism raised the question as to the validity of aeration during cold periods.

Sludge settling tests in Alaska (71) demonstrated that the settled solids did not undergo significant decomposition in the winter but did in the summer. Biological decomposition was found to follow the Van't Hoff-Arrhenius relationship between 0.5° and 20°C. The oxygen demand was 1.49 times the BOD removed. Measurement of settled sludge from the Eielson Air Force Base aerated lagoon indicated that solids would concentrate to 9.1% with 87% volatile solids. It was felt that onehalf inch accumulation of sludge could be expected yearly.

Design of aerated lagoons under low temperature conditions has been examined recently (72-74). Deep lagoons are preferred to shallow lagoons because of heat loss characteristics. Experience has shown that the perforated plastic tubing clogs easily. Hydrochloric acid for cleaning the plastic tubing has been used but is short lived and poses a definite problem. Large bubble air diffusers create less operational problems. Two cells in series give better effluent quality than single cells. From the experience to date diffused aeration is preferrable to mechanical surface aeration. BOD reduction is related to aeration time and temperature. To maintain a high degree of treatment, 80-90% BOD reduction, the aeration time must be increased as the temperature decreases. The BOD reduction in the summer is controlled by the production of algae in the effluent. With proper design, aerated lagoons can perform satisfactorily at low temperatures. Currently, there are 17 aerated lagoons in operation in Alaska and many more are in operation in Canada. The key is proper design.

DESIGN CONCEPTS

At the present time no state has any published criteria for the design of aerated lagoons. By and large aerated lagoons have either evolved by trial and error or have been designed from the concepts of Eckenfelder and O'Conner (3) or McKinney (5). Over 100 aerated lagoons have been constructed in the United States during the past decade; but few studies have been made to develop sound design criteria. Correlation of published data with fundamental concepts of biological treatment offers a sound approach to develop basic design criteria for aerated lagoons.

Part of the problem with aerated lagoons has been the failure to apply the fundamental concepts of biological waste treatment together with sound hydraulic concepts. Actually, there are three variations of aerated lagoons: completely mixed, facultative and aerated oxidation ponds. This classification by Benjes (11) is very important in developing sound design criteria. The failure to recognize these modifications has been a serious source of confusion in evaluating design criteria.

WASTE CHARACTERISTICS

The first step in designing any waste treatment system is to determine the waste characteristics. Too often generalized waste characteristics are so vague that the actual wastes have no real relationship to the plant design. The net result is poor operations. Of primary concern are the BOD and the suspended solids. Secondarily, nitrogen and phosphorus are assuming greater importance. It should be recognized that wastes can be essentially soluble or a combination of soluble and suspended solids. These two types of wastes have significantly different characteristics as far as aerated lagoons are concerned even if their total BOD is the same.

Domestic sewage generally has a 5 day BOD between 200 and 400 mg/l with from 200 to 500 mg/l suspended solids. Whereever possible, analysis of domestic sewage should be made prior to developing design criteria. Where direct analyses of wastes are not possible, reasonable estimates must be made of the basic criteria. For small communities a BOD value of 200 mg/l and a suspended solids value of 240 mg/l is reasonable. For new subdivisions the BOD value of 240 mg/l and a suspended solids value of 300 mg/l is adequate. The relationship between soluble and suspended BOD generally changes with the length of time in the sewer system. Very fresh sewage may have 75% of the BOD in suspended form; while septic sewage can have less than 50% of the BOD as suspended solids. Normal domestic sewage can be assumed to average 60% suspended BOD unless more definite data are available. The suspended solids in domestic sewage are generally 80 to 85% volatile. Approximately 40% of the volatile suspended solids are non-biodegradable. This non-biodegradable fraction of suspended solids has been a primary source of error in biological treatment plant design in the past. The non-biodegradable suspended solids and the inorganic suspended solids must either be removed by the treatment system or pass out with the effluent. These inert solids are not a problem with soluble industrial wastes.

EFFLUENT QUALITY

The effluent quality from any waste treatment plant is determined by the water quality requirements of the receiving stream. The current trend today is for a high degree of treatment, BOD and suspended solids less than 30 mg/l. For normal domestic sewage this means 85% BOD removal and an equivalent suspended solids reduction. Operational data indicate that aerated lagoons can meet these effluent requirements provided the metabolic reactions are complete and the suspended solids are removed.

The metabolic reactions are controlled by microorganisms, mixing, oxygen, and other environmental factors such as pH, temperature, and time. Turbulence required for rapid metabolism runs counter to good suspended solids separation. An independent solids separation system appears to be a necessity for high quality effluent from aerated lagoons.

Operational data have shown that aerated lagoons are not very efficient in removing nitrogen and phosphorus. Basically, nitrogen and phosphorus are removed by metabolism in biological systems with some adsorption into microbial surfaces a possibility. Removal of the microbial cells is needed for any significant nutrient reduction. Yet, minimum solids handling is one of the positive features of aerated lagoons. The failure to remove solids from aerated lagoons explains why aerated lagoons are not useful for nutrient removal.

COMPLETELY MIXED AERATED LAGOON

Design of the completely mixed aerated lagoon requires that adequate mixing is supplied so that the entire contents of the aeration tank are maintained in suspension. A minimum velocity of 0.5 fps must be maintained if microbial solids are to be kept in suspension. Mixing is normally generated by the aeration device, requiring a balance between the mixing function and the aeration function. To date completely mixed aerated lagoons have utilized mechanical surface aerators which aerate the mixed liquor by punping it into the air. The surface aerator favors a deep lagoon over a shallow lagoon. The deep lagoon, 10-15 ft., has a smaller surface area and better mixing characteristics than the shallow lagoon.

The aeration time is controlled by the rate of initial metabolism and the extent of endogenous respiration desired. The rate of initial metabolism is a function of the structure of the organic matter in the wastes as well as temperature. A simple organic waste is easier to treat than a complex waste. Soluble organics are metabolised more rapidly than insoluble organics. Aerated lagoons are easily affected by temperature with a change in rate of metabolism by a factor of two for each 10°C temperature change. Minimum temperature controls the rate of metabolism in the final design. At 20°C (68°F) the maximum rate of metabolism is approximately 240 mg/l BOD /hour. Since oxygen transfer and microbial separation are not practical at such high ratio of metabolism it is necessary to compromise on the aeration period. Considering normal variations in waste characteristics of domestic sewage, a 24 hour aeration period makes a convenient design period. The balance between power requirements for oxygen transfer and for mixing indicates that complete mixing aerated lagoons are optimum around 24 hours aeration capacity (11). Below 24 hours aeration oxygen transfer controls; while power for mixing controls above 24 hours.

With a 24 hour aerated lagoon, the lagoon acts as a surge tank to level out the oxygen demand peaks. Yet, it must be recognized that the peak oxygen demand must be met when it is added to the aerated lagoon. The peak hourly BOD load for domestic sewage is generally less than 200 percent of the average hourly BOD load. Considering a domestic sewage of 200 mg/l, the peak BOD load will be 16.7 mg/l/hour. The oxygen demand rate will be created by the metabolism of the incoming wastes and the endogenous respiration of the microbial cells in the mixed liquor. The oxygen demand rate related to the metabolism of the peak BOD load can be estimated as being equal to 0.5 the BOD load rate, 8.4 mg/l hr in this example. The endogenous rate can be determined from the active cells in the aeration tank. With completely mixed system, the average concentration of active microbial cells can be calculated from the following equation:

$$Ma = \frac{K_s Fi}{KmKet + Km + Ke + \frac{1}{t}}$$

where Ma = average active mass of microbes, mg/lVSS

Fi = average influent BOD, mg/l

t = aeration time, hours

Km = metabolism factor, 15/hr @ 20°C

Ks = synthesis factor, 10/4/hr @ 20°C

Ke = endogenous respiration factor, 0.02/hr @ 20°C

SinceKe and $\frac{1}{t}$ are small compared to Km and Ks, this equation can be simplified as follows:

$$Ma = \frac{0.7\ Fi}{(Ket+1)}$$

The various factors, Km, Ks, and Ke, are dependent on temperature and change by a factor of two for each 10°C tempearture change from 20°C. With 24 hours aeration at 20°C, Ma = 0.47 Fi. At 30°C, Ma = 0.36 Fi; and at 10°C, Ma = 0.56 Fi. For the domestic sewage example, Ma would be 112 mg/l VSS at 10°C, 94 mg/l VSS @ 20°C,and 72 mg/l @ 30°C.

The endogenous oxygen demand rate can be calculated from the following equation.

$$\left(\frac{do}{dt_e}\right) = 1.14\ KeMa$$

In the domestic sewage example the endogenous oxygen demand rate would be 1.3 mg/l/hr at 10°C, 2.1 mg/l/hr at 20°C, and 3.3 mg/l/hr at 30°C. The peak oxygen demand rate can be calculated as the sum of the metabolism demand plus the endogenous demand; 9.7 mg/l/hr at 10°C, 10.5 mg/l/hr at 20°C, and 11.7 mg/l/hr at 30°C. It can easily be seen that the peak oxygen demand will have to be met at the maximum temperature of the aeration system.

The oxygen transfer characteristics of any aeration system can be determined from the following equation.

$$\frac{do}{dt} = \alpha\ K_L a\ (BO_s - 0)$$

where $\frac{do}{dt}$ = oxygen demand rate, mg/l/hr

O_s = oxygen concentration in water at saturation, mg/l

O = oxygen concentration in the aeration tank, mg/l

α = oxygen transfer coefficient in mixed liquor

B = oxygen saturation coefficient in mixed liquor

K_La = oxygen saturation transfer rate coefficient, 1/hr.

With raw sewage α and B are less than 0.5 normally. As the microbes purify the wastes, the values of α and B approach unity. In properly operated aerated lagoons treating normal domestic sewage, α of 0.9 and B of 0.95 are reasonable. At 20°C K_La should be 1.34/hr at sea level. It is important that the aerator meets the desired K_La and the minimum velocity of 0.5 fps at the fartherest point from the aerator. Proper pumping of the fluid into the air can both move the fluid and transfer the oxygen. It appears that a pumpage of 415 cfm/HP is close to the maximum pumpage that can be expected from a mechamical aerator at the present time. As the horsepower of the aerator increases, the pumpage per unit of power expended decreases. Thus, it is normally more economical to use several small units than one large unit. The use of multiple units has value in operations as the impact of a mechanical failure will be proportionately reduced. Each separate design must be evaluated on its own merits as there is no simple guide for aerator selection.

The effluent BOD is determined by the unmetabolised wastes passing through the aeration unit and endogenous respiration of the active microbial mass. The unmetabolised waste BOD for a 24 hour aeration or longer aerated lagoon will be less than 1.0 mg/l carbonaceous BOD. In effect, the microbial solids form the BOD in the effluent. The carbonaceous BOD for the effluent suspended solids can be determined from the following equation.

$$\text{Eff. BOD} = 0.8\ \text{Ma (C only)}$$

Nitrification related only to the nitrogen released during endogenous respiration could increase the BOD in the effluent.

$$\text{Eff. BOD} = 1.12\ \text{Ma (C+N)}$$

Evaluating the system for 24 hours aeration at 20°C, the BOD values can be expressed in terms of the influent BOD.

Eff. BOD = 0.38 Fi (C only)
Eff. BOD = 0.52 Fi (C+N)

Thus, one should expect from 48 to 62% BOD reduction in a properly designed, completely mixed aerated lagoon with 24 hours aeration at 20°C. Greater BOD reduction could be expected with separation of the microbial solids.

Unfortunately, the dispersed characteristics of the microbial solids precludes rapid flocculation and sedimentation. The unmetabolised microbial solids pose a problem of further stabilization. Originally, it was recommended that an oxidation pond be placed after the aerated lagoon to permit the microbial solids to settle and be stabilized. The inorganic elements remaining will stimulate the algae to grow up in the oxidation pond. The BOD and suspended solids in the final effluent will be determined by the algae and not by the microbial solids discharged from the aerated lagoon. Maximum removal of algae requires at least a two cell oxidation pond with series operation. A rock filter at the effluent end of the oxidation pond will assist in removing excess algae and will produce the highest quality effluent with a minimum of effort.

If land is limiting, it is possible to place several aerated lagoon cells in series to produce maximum degradation prior to discharge to sedimentation pond. The sedimentation ponds can be quite small when compared with the conventional oxidation pond utilized directly after the aerated lagoon. The sedimentation ponds can be quite deep, 8 to 10 ft., when compared to the depth of oxidation ponds, 3 to 4 feet. This increased depth permits sludge storage until the sludge can be removed and placed on the land.

Normal oxidation ponds have a loading rate of 40 pounds BOD /acre/day. The 24 hour aerated lagoon-oxidation pond combination has an area approximately 40% the area of an oxidation pond for treating the same volume of wastes.

Addition of a second aerated lagoon in series with the first aerated lagoon would reduce the active microbial mass by 2/3. A third aerated lagoon would probably reduce Ma approximately 2/3 of that in the second aerated lagoon. Thus, the three celled aerated lagoon system would result in an effluent with around 10 mg/l BOD. The final solids separation cell can be of 1 to 5 day capacity depending upon the desired frequency of cleaning of the sedimentation pond. This system would greatly reduce the land area required but would require more carefully constructed tanks and aeration equipment. The aerator design would be based on mixing and not on oxygen transfer. The oxygen demand in the second and third aerated lagoons would be low compared with the first aerated lagoon.

The effluent suspended solids from the first aerated lagoon will be composed of the active microbial mass (Ma), the endogenous mass of dead cells (Me), the inert, inorganic mass (Mii), and the inert organic Mass (Mi). As indicated previously, the active microbial mass (Ma) is a function of the food added to the system. The endogenous mass is a function of the active mass (Ma) and the aeration time. Approximately 20% of the organic matter synthesized during metabolism cannot be biodegraded in the aeration tank and remains as inert volatile matter in the form of dead microbial cells (Me).

$$Me = 0.2\ KeMat$$

With a 24 hour aeration unit at 20°C the endogenous mass (Me) will equal 0.1 Ma. It is possible to express both Ma and Me in terms of the incoming BOD (Fi).

$$Ma + Me = 0.52\ Fi$$

The inert inorganic solids (Mii) in the mixed liquor and in the effluent will be the sum of the inert inorganics in the raw wastes plus 0.1 (Ma+Me) which was formed from soluble ions during microbial synthesis.

$$Mii = Mii \text{ in raw waste} + 0.1\ (Ma+Me)$$

Normally, Mii in raw wastes will be approximately 20% of the total suspended solids.

$$Mii = 0.2\ M \text{ in raw wastes} + 0.05\ Fi$$

With domestic sewage Mii will be approximately 60 mg/l in a 24 hour aerated lagoon at 20°C.

The inert organic solids (mi) normally average 40% of the raw waste volatile suspended solids. In terms of total suspended solids in the raw waste Mi will be approximately 32%. For domestic sewage Mi will be from 75 to 80 mg/l. Thus, the inert solids in domestic sewage can be expected to be around 140 mg/l, 58% of the suspended solids in the raw wastes. When Ma and Me are added to Mii and Mi to form the total suspended solids (M_T) in the system, M_T will average essentially the same as the influent. It is little wonder that some engineers have felt that this fact demonstrated that suspended solids in domestic sewage were not biologically degraded. Actually, the microbes metabolised the biodegradable organic suspended solids but metabolism of soluble organics produced additional suspended solids. The net effect is no apparent change in suspended solids while there is actually a change in type of solids.

The actual reduction in mass in the second aerated lagoon will be only 0.8 the change in Ma since Me produced will equal 0.2 the change in Ma. With normal domestic sewage the decrease in the total suspended solids will be 50 mg/l. The decrease in the third aerated lagoon would be less than 20 mg/l suspended solids. The total solids reduction with three 24 hour aerated lagoons would be approximately 30%. The remaining sludge could be concentrated to 1.5 to 2.0% in the sedimentation cells. Storage should be sufficient to hold solids during winter period.

A recent study (75) in Canada attempted to evaluate the CMAS equations presented in this section as well as the equations developed by Eckenfelder. The Canadian study examined data from two aerated lagoons which had been in operation for several months. The aerated lagoon at Windsor was constructed in 1965 with 4 days retention at an average flow of 60,000 gallons per day. The loading rate was 20 lbs BOD/100 cf/day and a 20 HP fixed surface aerator was used. The town of Durham had a 4.2 day retention at an average flow of 290,000 gallons per day. The BOD loading was only 3 lbs BOD/1000 cf/day with four-5 HP fixed surface aerators. It was concluded that the CMAS equations presented in this design section were reasonable provided introgenous metabolism was considered. On the other hand, Eckenfelder's equatons were very specific for each type of waste and required individual evaluation. They cautioned that the general application of either method should not be considered unless the design engineer is well aware of the design limitation of biotreatment. There is no doubt that design equations must be evaluated against field results to determine their usefulness, but it is important that they are properly evaluated. As pointed out previously, CMAS units should be designed on the basis of short term aeration, 24 hours, if they are to be truly completely mixed. Although, designed as CMAS units, these two plants studied were not completely mixed and could not be expected to check the CMAS equation exactly. The data presented showed that the system was not completely mixed or that the data was not representative of the wastes entering the plant. It was apparent that adequate power was not available for complete mixing with the aerator employed. In effect, these two aerated lagoons were actually facultative aerated lagoons rather than being completely mixed aerated lagoons. Engineers are to be cautioned to use proper design criteria and proper evaluation of operational data. Improper evaluation of operational data such as occurred in this Canadian study can create misimpressions as to the validity of sound design concepts. Since the article cannot be removed from print or corrected, it will continue to cause misunderstanding for years to come.

The completely mixed aerated lagoon can produce the desired effluent, 85% BOD and suspended solids reduction, with a 24 hour aeration period aerated lagoon combined with a normal stabilization pond and terminal rock filter or two additional 24 hour aerated lagoons with a one to five day retention, deep sedimentation pond.

FACULTATIVE AERATED LAGOON

Most aerated lagoons constructed to date would have to be classified as facultative aerated lagoons. Basically, facultative lagoons are designed with long aeration periods, 7 to 20 days. The aeration equipment is designed to transfer the theoretical oxygen demand but is too small to keep the solids in suspension. The net effect is for all heavy solids to settle out in the aeration cell. Only the dispersed microbes are maintained in suspension with the soluble organics. The microbial reaction is dependent upon the contact time within the aeration zone. The organic matter which settles to the bottom of the aerated lagoon undergoes anaerobic metabolism and slowly releases organics into solution. The solids sedimentation and anaerobic decomposition makes scientific evaluation of facultative aerated lagoons all but impossible. Soluble wastes will react differently than wastes with high concentrations of suspended solids. Thus each waste must be evaluated separately.

Experience has generally favored 70 to 80% BOD reduction with facultative aerated lagoons having 4 to 8 days retention. Normally, aeration equipment has been sized on 1.5 to 2.0 lbs O_2/HP-hr without regard to mixing. The oxygen requirements have been determined from the total oxidation of the wastes at 1.5 pounds of oxygen per pound of BOD added. The results of the facultative aerated lagoon are highly variable and subject to considerable temperature effects. The rate of reaction changes by a factor of two for each 10°C temperature change.

The advantage of the facultative aerated lagoon lies in the fact that both biological stabilization and solids separation occur in the same pond. Adequate volume must be provided for sludge storage so that sludge removal can be accomplished at infrequent intervals. It must be recognized that sludge removal is an essential part of the facultative lagoon design.

The disadvantages of the facultative aerated lagoon is the lack of control over the biological process. The microbial growth is slow because the microbial population is low. In effect, the microbes move from a favorable growth environment to an unfavorable environment as they move from the aerobic mixing zone to the quiescent zone. There is a continuous intermix between the volume of fluid around the aeration unit and the adjacent fluid. Maximum microbial growth efficiency can be achieved only with complete mixing of the aeration tank contents. As the organic solids accumulate in the aerated lagoon, the unmetabolised load accumulates and creates periodic overloads and resulting odor nuisances. Unfortunately, facultative lagoon performance cannot be predicted accurately, making scientific design impossible. The operational characteristics of each facultative aerated lagoon are a surprise to the design engineer, the owner, and the regulatory authorities. Experience gives a few rough guidelines but no specific design criteria.

AERATED OXIDATION PONDS

The overloading of oxidation ponds resulted in the development of aerated oxidation ponds; i.e., oxidation ponds to which diffused air was added over a large portion of the pond area. More often than not, municipalities employing oxidation ponds continue to load until odor nuisances create sufficient complaints to require action. Needless to say, these municipalities demand instant solutions and are quick to blame the engineers for not producing instant answers. The problem was a simple one to define but a difficult one to solve. Overloading the oxidation pond could be alleviated by the addition of oxygen; but the problem was one of distributing the oxygen over the very large area of the oxidation pond. In recent years, the popularity of diffused aeration systems for overloaded oxidation pond systems has increased tremendously and is being extensively employed.

Oxidation ponds stabilize the organic matter in the wastewaters through the action of bacteria which metabolise aerobically if the system is to be relatively odor free. The inorganic componants of the wastewaters stimulate the growth of algae at the surface of the ponds. The algae release oxygen which the bacteria can use; but in producing oxygen, the algae also produce organic matter that must be stabilized. In most oxidation ponds the oxygen demand by the algae in the dark far exceeds the oxygen demand by the bacteria in stabilizing the wastewaters. As the load on a given oxidation pond exceeds the oxygen capacity of the algae under relatively quiescent conditions, improvement can be made by the addition of additional oxygen or by mixing to permit more efficient growth of the algae. Mixing permits the algae to be carried from the surface down into the lower portion of the pond. Some of the algae settle out on the pond bottom and are removed from the reaction system. Fresh nutrients are carried to the surface where additional algae growth and oxygen production results. Without removal of the algae, the effluent quality of the higher loaded oxidation pond will be increased; but there will be no odors. Two cell ponds and tapered mixing helps distribute the algae over the system so that some settling occurs near the end of the pond system.

The vague characteristics of the algae phase of the oxidation pond makes it difficult to design the aerated oxidation pond with assuracne of the results to be obtained. Generally, the aerated oxidation ponds are designed to accept the full organic load by the aeration equipment without concern for the activities of the algae. The important aspect of the aerated oxidation pond is the fluid pumpage. Each type of diffused aeration equipment must be evaluated on its own merits since each system has its own specific characteristics. Experience has indicated that a fluid turnover time of 5 minutes in the waste influent area and 20 minutes near the waste effluent area is more than adequate. The controlling factor in the design is the oxygen demand rate in the dark. Adequate oxygen must be available to meet the oxygen demand from both the bacteria and the algae.

Experience has indicated that deep aerated oxidation ponds are more efficient than shallow aerated oxidation ponds. Where possible, aerated oxidation pond depths are increased to 10 ft. to give improved mixing and oxygen transfer characteristics. Plastic tubing is spaced at 5 ft. centers at the influent end and 20 ft. centers at the effluent end. Air is supplied with a positive displacement air compressor operating at 9 psi pressure. Normally, air is supplied at the rate of 700 cubic feet per day per pound of BOD. Since calcium carbonate type deposits form around the small orifices in the plastic tubing, it is necessary to clean out the plastic tubing at periodic intervals, normally at 3 month intervals. Gaseous hydrochloric acid is used for cleaning the orifices. Approximately 2 lbs of HCl gas is required for each 1000 ft. of tubing. The dilution of HCl in the pond is adequate to prevent any adverse conditions from developing.

A second type of diffused aeration system employs air discharge below a round tube with the tube acting as an air life pump to create circulation and aeration at the same time.

The spacing of the tubes is dictated by the magnitude of the organic load and the degree of mixing desired. The air tubes utilize approximately 10 scfm air per tube which are spaced at 10 ft. centers. Liquid depths with the air tubes normally are 15 feet to insure maximum mixing for minimum air. Data has indicated an oxygen transfer capability of 1.5 lbs/hr/gun. Because of the specific nature of the equipment required for aerated oxidation ponds, each manufacter must be contacted for specific design criteria. Engineers should be cautioned that equipment manufacturers have a tendency to be overly optimistic about the operational characteristics of their equipment.

Where aerated oxidation ponds have been designed as such initially, the retention period will normally be at least 30 days at full design load. The fact that aerated oxidation ponds are 2.5 to 3 times deeper than conventional oxidation ponds; the surface area loading appears higher than normal. Since surface area has little significance in aerated oxidation ponds, engineers should not be concerned with surface area loading design factors. The overall BOD reduction is related to removal of suspended solids as indicated previously. There is no specific BOD reduction that can be predicted for aerated oxidation ponds at the present time. Current research into suspended solids reductions would indicate that a high degree of BOD reduction is possible, at least 90% where the effluent suspended solids are reduced below 20 mg/l.

RESEARCH NEEDS

Research on aerated lagoons is needed to examine the various types of aeration equipment. Field studies are needed to determine the actual quantities of oxygen transferred and the mixing produced both in the primary zone, immediately around the aerator, and in the secondary zone beyond the primary zone. Little information is available on pond design and aeration equipment design. The net result is that aerated lagoon design lacks scientific design aside from the completely mixed aerated lagoons.

The removal of suspended solids from aerated lagoon effluents deserve further study the same as with oxidation ponds. Short retention period sedimentation ponds designed to minimize wind mixing should be evaluated as a method for producing satisafctory effluents. Multicell ponds should also be evaluated as final polishing units for aerated lagoon effluents.

Methods for solids removal from aerated lagoons needs investigating. Since solids settle in the aerated lagoon and accumulate at a faster rate than in oxidation ponds, provision must be made for periodic solids removal. To date no research has been carried out on removal and disposal of solids in aerated lagoons.

Further research is needed on the temperature effects on aerated lagoons. The lack of solids separation and sludge return to the aerated lagoon makes it more vulnerable to temperature variations. The temperature effects would be more significant in completely mixed aerated lagoon since the retention period is very short compared with the facultative aerated lagoon.

Operational evaluation is needed on existing aerated lagoons to permit the building up of a data base from which to evaluate aerated lagoon design and operation. The lack of adequate data is a major deficiency in aerated lagoon design development.

Aerated lagoons represent an intermediate treatment system between oxidation ponds and activated sludge. There is a real need for good aerated lagoons but further research is needed before we develop aerated lagoon technology to the level required to meet future water quality criteria.

CONCLUSIONS

The current state of the art for aerated lagoons indicates that engineers have not utilized the fundamental concepts of biotreatment systems to arrive at sound design criteria. Several hundred aerated lagoons have been constructed in the United States during the past decade with little scientific basis for design. These aerated lagoons have performed reasonably well considering how they were designed, constructed, and operated. Yet, with proper application of sound biotreatment design fundamentals most of these plants could have been better designed so that they would have produced a superior effluent quality to that being produced.

Proper design of aerated lagoons requires a balance between the waste load, the microbes, mixing, oxygen and retention time. The complete mixing aerated lagoon with a 24 hour aeration period represents the optimum system for domestic sewage. With 24 hours retention the aeration system balances the most efficient utilzation of energy for mixing and oxygen transfer. The system has sufficient capacity to absorb shock load variations and still permit complete metabolism without nitrification becoming a major factor in effluent quality. The fundamental problem with the 24 hour aerated lagoon is proper separation and disposal of suspended solids.

short term, deep sedimentation ponds, rock filters, or sand filters are needed to produce BOD reductions in excess of 50%. It is possible to obtain 90% BOD reduction from aerated lagoons provided the suspended solids are removed. Oxidation ponds following 24 hour aerated lagoons are not desirable because of the large algae production that will result.

Facultative aerated lagoons have been the primary type of aerated lagoons constructed to date. Surface aeration equipment have been placed in large ponds having several days retention to produce localized aeration. The mixing is not adequate for maintaining solids in suspension. The net result is that solids settling occurs in the quiescent sections of the facultative aerated lagoons. Algae growth also occurs in facultative aerated lagoons. Although most facultative aerated lagoons are designed on the basis of total oxygen demand, there is no way to predict the effluent quality. Experience has yielded from 60 to 90 percent BOD reduction depending upon the individual design. Review of operational results did not produce any valid design concepts that can be applied to facultative aerated lagoons.

The third form of aerated lagoons is the aerated oxidation pond. Aerated oxidation ponds have resulted from the need to add oxygen to overloaded oxidation ponds in as simple a fashion as possible. Diffused aeration through plastic tubing or round, vertical tubes produces slow mixing which permits more efficient growth of algae and better distribution of the oxygen resources throughout the pond. Two cells are usually required to produce some separation of the algae produced during the rapid metabolism of the waste matter. Normally, 30 days retention are required for aerated oxidation ponds designed from scratch. Longer periods are available in overloaded oxidation ponds. With separation of algae 90 percent BOD reduction is possible. The effluent quality from aerated oxidation pond will be a function of the suspended solids in the effluent. Essentially, the diffused aeration eliminates the odor nuisances from overloading and serves as a temporary treatment process until a more permanent system can be designed and constructed.

With increased emphasis on maximum effluent quality, aerated lagoons as they have been used in the past will have to be modified to produce the effluent quality desired for the future. It should be recognized that with minor modifications all three types of aerated lagoons can produce better than 90% BOD reduction. Because of their simplicity of design and operation aerated lagoons are going to play a definite role in the treatment of liquid wastes from small municipalities and small industries. The key to success is the proper application of basic fundamentals.

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SECTION VI

ANAEROBIC LAGOONS

Anaerobic lagoons were the inevitable result of the widespread use of stabilization ponds. Increased organic discharges and the need for greater economy pushed lagoon loading rates higher and higher, eventually exceeding the natural stabilization capacity of the ponds. Failures resulted. Failures were not recognized, however, by the usual criteria of poor effluent quality although this too occurred. Odors proclaimed the failures to everyone, expert and layman alike, and nuisance complaints were the result.

Anaerobic lagoons, however, are more than overloaded stabilization ponds. They are units intentionally designed to create anaerobic conditions for the purpose of accomplishing the desired destruction of organic matter and the stabilization of wastewaters. Experience has shown that anaerobic lagoon designs which create the basic conditions favorable to complete digestion will accomplish stabilization of wastewaters without nuisance odors.

High-temperature high-strength wastewaters are particularly amenable to treatment by anaerobic lagoons. As a result, they have been used extensively for certain industrial waste such as those from the meat packing industry. However, anaerobic lagoons have also been used from Australia to Canada to successfully treat municipal wastewaters, generally as pretreatment units followed by oxidation ponds. The process has also been widely applied to the treatment of slurries of animal manure originating from confined livestock feeding operations. Lagoons treating animal manures, although accomplishing anaerobic stabilization of organic matter, seldom, however, receive sufficient flow to result in a wastewater effluent.

The treatment efficiency of anaerobic lagoons may range from 25 to 90% although units operating satisfactorily will generally accomplish a 60 to 80% BOD reduction. High concentrations of BOD, suspended solids, and sometimes hydrogen sulfide occur in the effluents depending upon the initial characteristics of the incoming wastewaters. BOD concentrations of 100-500 mg/l in the effluents of anaerobic lagoons are common; and, as a result effluents must receive further treatment prior to discharge to a receiving body of water. Usually the additional treatment is provided by oxidation ponds.

All lagoons designed to function anaerobically have not, however, performed in an acceptable odor-free manner. In some cases the reasons for the failures are clear while in other cases the cause of failure is not apparent. Design

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criteria that have proved satisfactory for some areas with certain wastewaters have resulted in miserable failures when inappropriately applied to other wastewaters and climatic conditions.

Designs which failed to create a wastewater environment favorable to anaerobic digestion with gasification were destined to failure. Inappropriate attention to basic factors including temperature, pH, the nature of the organic material, and the dispersion and mixing of these organics with properly acclimated organisms probably were the cause of many failures. Other failures remain unexplained.

The following section reviews the existing design criteria and operating experiences for anaerobic lagoons. Modifications in designs reported in the literature are noted. The underlying fundamental principles that govern the success or failure of anaerobic lagoons are summarized and areas of needed additional information that will result in efficient trouble-free and nuisance-free wastewater systems to provide the best treatment at the lowest cost.

Development of Design Criteria

The design criteria that exist for anaerobic lagoons are impirical in nature. The successes and failures of earlier lagoons in a particular region have served to provide the guidance for future designs.

Parker *et al*. (1) were among the first to advocate the advantages of a pond system designed specifically to operate as an anaerobic unit. Studies conducted in Melbourne, Australia on anaerobic lagoons 3 ft deep with a 2-5 day detention revealed that BOD removals up to 600 lb per day/acre occurred at summer temperatures (64°F). Removals of 450 lb BOD per day/acre occurred in the winter (52°F). The treatment in the anaerobic lagoons was attributed to both sedimentation and digestion; however, the comparably high BOD removal efficiency was considered to be dependent upon the development of a digesting sludge layer.

Continued experience with anaerobic lagoons in Australia resulted in design criteria for that region. Considering normal strength sewage, it was reported (2) that anaerobic lagoons would provide about 60 to 70% BOD removal with design BOD loadings of 900-1200 lb per day/acre and 675 lb per day/acre in winter. Lagoon depths of 3 to 5 feet were standard at that time. Occasional extreme odor nuisances occurred at these loadings particularly at the commencement of operation of new units, although a certain amount of odor was normally present. Removal of solids accumulations were required only at 6 to 10 years intervals.

In the U.S.A. satisfactory experiences with a pilot plant in the early 1950's led to the design by Sollo (3) of an anaerobic pond to treat meat packing wastes at Moultrie, Georgia. Loading of the unit was computed on a volume basis in recognition of its similarity to a sludge digester. Average data reported for the pilot unit revealed that a BOD reduction of 65% occurred with a 4.6 day detention period and a BOD loading of 11.2 lb/1000 cu ft/day. The full scale anaerobic pond had a water depth of 14 ft and a surface area of 1.4 acres and recirculation of lagoon contents was provided. During the first four years, BOD concentrations were reduced from an average of about 1100 mg/l to 160 mg/l through the anaerobic lagoon, a removal efficiency of about 85%. Heating facilities for the lagoon were not provided and it was noted that as pond temperatures dropped below 75°F a reduction in removal efficiency could be expected.

Following these early studies by Sollo, wide spread application of anaerobic lagooning was found in the meat industry. These anaerobic lagoons were generally designed on an organic loading basis of 15 to 20 lb BOD/1000 cu ft/day, usually with 15 ft depths. In most cases these lagoons were designed to function in areas with more severe climatic conditions than those of Georgia. Pretreatment, such as grease removal was frequently provided. BOD removal efficiencies of 60 to 80% were expected and in most cases the effluents were discharged to aerobic stabilization ponds for additional treatment. Design criteria as reported for several systems treating meat wastes are given in Table 5.

Coerver (4)(5) reported that design criteria for anaerobic lagoons serving small abattoirs and packinghouses in Louisiana had been developed with a somewhat different approach. Three small ponds in series were layed out to receive the wastewaters from the abattoirs. The first pond was anaerobic and received all the wastes from the slaughtering including blood and paunch manure. This pond was designed on the arbitrary basis of one acre foot for each 500 hog units of slaughtering per week. Pond depths were usually limited to 2 to 3 feet to accommodate high ground water conditions.

In the 1960's, lagoons were coming into vogue in the animal production industry. Water carried manure handling systems were being designed to serve confined feeding operations for poultry, swine, and cattle. These early lagoons were often designed and constructed to receive the manure slurries without consideration being given to the characteristics of the

Table 5

Criteria Used for the Design of Anaerobic Lagoons Treating Meat Wastes

Reference	BOD Loading lbs/1000	Cells	Depth ft	Detention days	Recirculation
(6)	20*	2-series	15	5.12	Yes
(7)	15	1	--	----	Yes
(8)	15	2-parallel	15	4.5	No
(9)	15	2-parallel	15	----	No
(10)	--	3-parallel or series	18-20	3-5	Yes

*Minimum temperature of 75°F. specified.
**Extensive pilot studies preceeded design.

animal waste or the principles involved in its destruction. Suggested design criteria was mistakenly patterned after that of early aerobic lagoons.

Following field studies of operating lagoons, Dornbush and Andersen (11) discussed certain environmental factors and suggested an arbitrary design limit of 5 to 10 lbs of volatile solids per 1000 cu ft of lagoon for South Dakota conditions. The temperature considerations were considered critical and water depths of 5-8 feet were suggested.

The results of extensive investigations of animal manure characteristics and treatment of manure slurries in anaerobic lagoons have been published by Hart (12)(13) and Loehr (14)(15)(16)(17). Hart (12) reported design criteria for lagooning of animal wastes in terms of cubic feet per animal recalculated from results of several investigators in different climatic locations. These data are presented in Table 6. Performance of animal waste lagoons was judged largely in terms of freedom from odors.

Animal waste lagoons are designed for the special purpose of destruction and stabilization of organic manures. Solids accumulate until they require removal but there is seldom an overflow of liquid to create a water pollution problem.

Anaerobic lagoons have been widely accepted in regions of Canada for the treatment of municipal wastewaters. By 1966 there were 69 communities in Alberta, Canada using anaerobic ponds (10). In Canada the anaerobic ponds are termed "short detention" ponds and have detention periods ranging from 2 to 4 days with liquid depths maintained at 8 to 10 ft. Maximum organic loadings that are permitted are 4000 lbs BOD/acre/day when the liquid depth is 10 feet (21). This may be compared with the design organic loading rate of from 30 to 50 lb/acre/day for the secondary ponds to which the short detention pond effluent is discharged. Other studies (22) have suggested that depths to 15 ft would be desirable in Canada where conditions permitted, and that the outlet be located about 5 ft below the liquid surface. Depths 18 to 20 ft were used by Stanley (10) to conserve heat at Edmonton, Canada.

Following extensive studies of lagoons in California, Oswald (23) has maintained that methane fermentation within anaerobic lagoons may be regarded as the sine qua non of nuisance free anaerobic pond performance. As a result, he contended that to design an anaerobic lagoon that will be odor-free, the design must result in environmental control with conditions favorable to methane fermentation. An important factor would include an adequate population of methane forming bacteria

Table 6

Manure Stabilization Pond Loading Rates (18)

Researcher(s), Location	Recorded Loading Rate	Recalculated Loading Rate cu ft/animal	Evaluation of Performance
		SWINE	
Clark, Illinois (18)	4-20 ft^2/hog 3-10 ft deep	40-60 cu ft/hog	Malodorous, unsatisfactory
	550 hogs/acre-year, 5-7 ft deep	475 cu ft/hog	Satisfactory
Dornbush & Andersen South Dakota (11)	130-170 cu ft/hog	130-170 cu ft/hog	Satisfactory
Hart & Turner, California (13)	45 & 67 cu ft/100-lb pig	45 & 67 cu ft/100 lb animal	Somewhat, but not excessively, odorous
	124 cu ft/100-lb pig	124 cu ft/100-lb animal	Satisfactory
		POULTRY	
Dornbush & Andersen South Dakota (11)	3.64 ft^2/chicken less than 2 ft deep	5.5 cu ft/hen	"Vile odors"
	3.64 ft^2/chicken 4 ft deep	14.6 cu ft/hen	Much better

(Continued) Table 6

Researcher(s), Location	Recorded Loading Rate	Recalculated Loading Rate cu ft/animal	Evaluation of Performance
Cooper, California(19)	575 lb BOD/acre-day; 1.09 ft^2/hen 5-6 ft deep	6 cu ft/hen	"No odor"
Hart & Turner California(13)	8.35 cu ft/hen	8.35 cu ft/hen	Very malodorous
	13.6 cu ft/hen	13.6 cu ft/hen	Satisfactory
	49.8 cu ft/hen	49.8 cu ft/hen	Algal-laden pond, satisfactory but overdesigned
		CATTLE	
Witzell et al., Wisconsin(20)	60 ft top diameter 40 ft bottom diameter 5 ft deep-6 bulls	1,547 cu ft/bull	Satisfactory
Hart & Turner California(12)	$\frac{795,\ 1{,}000,\ \&\ 1{,}830\text{ cu ft}}{1{,}000\text{-lb animal}}$	$\frac{795,\ 1{,}000,\ \&\ 1{,}830\text{ cu ft}}{1{,}000\text{-lb animal}}$	Satisfactory

to break down the organic acids resulting from the initial putrefaction of sludge solids accumulating on the bottom of the anaerobic lagoon. Other necessary environmental factors would include a temperature in excess of 15°C and preferably in the range of 32°C, a pH from 6.8 to 7.2, an alkalinity of about 2,000 mg/l and the complete absence of dissolved oxygen.

Oswald (23) reported that in California, the BOD loading necessary to create conditions in which anaerobic reactions predominate may be as little as 100 lbs/acre/day in the winter or as much as 400 lbs per acre/day in the summer. Greater depths and specific pond shapes have been suggested by Oswald. Increasing the depth of ponds to 12-14 feet will allow organic loadings up to 1,000 lbs/acre/day in the California climate.

These reports reveal the versatility of anaerobic lagoons. Municipal and industrial wastewaters and animal manure slurries have all been treated successfully. However, design criteria that have evolved appear to have a regional conotation and a wide variety of units have been used to express design loading rates.

The economic advantage of higher loading rates for anaerobic lagoons has been widely recognized and the expected BOD removal efficiency for anaerobic lagoons ranged from 60% upward in most cases. There, however, is one prime consideration that influences the design and acceptability of anaerobic lagoons more than any other single factor. This factor is the risk of ending up with a treatment unit that produces nuisance odors.

Operating Experience with Anaerobic Lagoons

A major advantage of ponds or lagoons for wastewater treatment is the minimal attention to maintenance and laboratory control that has been necessary for operation of these treatment facilities. This advantage has, however, been detrimental in evaluating the criteria used in design and the resulting performance of anaerobic lagoons. Reports of operating experience and resulting removal efficiencies have sometimes been based on short-term observations which may not have extended through the most critical climatic conditions. Valuable information has, however, been reported for a number of operating anaerobic lagoons treating municipal and industrial wastewaters.

Municipal Wastewaters - Evaluation of the long term results of operation of large anaerobic and aerobic lagoons to treat normal strength sewage were reported in 1959 by Parker et al. (2). Maximum summertime BOD removals by an anaerobic lagoon ranged from 578 to 1806 lb per day, acre which was in excess of the removal of 600 lb per day/acre reported earlier for experimental lagoons. BOD removal in the anaerobic units was generally 60-70% although it dropped to about 50% in winter. Winter BOD removals ranged from 420 to 540 lb per day/acre which approximated the experimental values of 450 lb per day/acre. Detention times were less than 5 days. Extreme odors occurred at the commencement of the operation of the anaerobic lagoons; however, the aerobic lagoons remained odor-free after receiving the effluent from the anaerobic units.

Parker and Skerry (24) have reported the loading and performance of three anaerobic lagoons treating municipal wastewaters in Australia during summer and winter conditions. Selected data are shown in Table 7. Samples of sludge solids collected at various points in the lagoons were characterized and related to lagoon performance and sludge depth. Sludge depths were observed to increase during the winters when biological activity and BOD removals were low. Higher effluent sulfide concentrations appear to have been associated with greater sludge depths. The lagoons were all constructed 3 to 3 1/2 ft deep. From the BOD data expressed as lb/day/acre, removals would appear to increase with an increase in loading.

An extensive summary of operating experiences including climatic conditions, design criteria, and operational problems and practices for waste stabilization ponds located in Canada has been reported by Fisher et al. (21). Intense odors from lagoons were generally associated with the spring ice break-up and anaerobic short-detention ponds tended to exhibit less intensive spring odors even though low intensity odors were emitted throughout the year. Excessive odor nuisance was associated with organic overloading of the pond, high sulfate water, and exposed sludge mounds.

Brisban et al. (22) have reported the results of detailed studies of anaerobic ponds treating municipal wastewater at two locations in Canada. At Moose Jaw, Canada, two ponds of 3.4 acres, each 10 ft deep, were operated as primary units with about 7 days detention and loading rates of 1080 lb BOD/acre/day. Anaerobic lagoon temperatures rarely exceeded 15°C in summer and dropped to near freezing in winter. Severe odors developed soon after start-up and persisted. Attempts to control odors by draining and flushing with secondary pond effluent revealed that a sludge mound

Table 7

Summary of Loading and Performance Data for
Anaerobic Lagoons Treating Municipal Wastewater in Australia (24)

Item	Werribee 145W		Wangaratta			Kerang
Season	Summer	Winter	Winter	Summer	Winter	Spring
BOD-mg/l						
Influent	448	407	358	270	222	190
Effluent	157	291	118	137	149	101
% Removed	65	28	67	49	33	47
Influent SS mg/l	436	436	394	---	---	323
Effluent						
Sulfide-mg/l	14	8	1.0	---	0.3	140
Dissolved O_2-mg/l	nil	nil	nil	3.8	nil	nil
pH	6.7	6.1	7.0	7.0	6.7	7.1
Water Temp. °C	20	15	15	24	12	21
Sludge Depth-in.						
Near inlet	17	24	10	10	14	30
Near outlet	14	27	7	9	14	30
BOD-lb/day/acre						
Loading	482	438	910	710	584	2800
Removed	313	125	630	350	192	1280

8 ft deep had accumulated after two years. The ponds were finally taken out of service during the summer because of odors. During intense odor periods removal efficiencies remained high: 70% for suspended solids, 55% for BOD, 60% for COD, 75% for grease and 90% for coliforms.

At the Sutherland lagoon site at Saskatoon, Canada (22), four anaerobic lagoons each 0.27 acres and 17 ft deep were operated at loadings that increased over a 3 year period from 1300 to 2600 lb BOD/ac/day or 3.7 to 7.0 lb BOD/1000 cu ft of initial volume. Although lagoon temperatures were comparable to those of the Moose Jaw lagoons odors were never a serious problem. Sludge accumulated to depths of 12.5 ft after 4 years at a rate of 0.014 cu ft/cap/day. Gas samples collected at the lagoon contained 58 to 64% methane.

Typical removal efficiencies for the two Sutherland anaerobic lagoons when operated in series were reported (22) as:

	Percent Removal	
	Winter	Summer
5 day BOD	35	50
Suspended Solids	70	70
COD	40	55
Grease	65	70
Coliforms/ml	80	90

After a four-year operating period, the reported percent removals were 10 to 20 percentage points lower. Possible explanations for the fewer odor problems at the Sutherland lagoon compared to those at Moose Jaw included the increased depth, the lower sulfate content of the sewage, the shorter lagoon detention time and the much smaller lagoon surface (22).

Industrial Wastes - Organic concentrations both solid and dissolved, of industrial wastewaters are frequently several orders of magnitude greater than those of municipal wastewaters. During recent years, certain industries, such as the meat processing, have recognized the inherant advantages of anaerobic lagooning and applied this process for the stabilization of high-strength organic wastewaters.

The present extent of application of anaerobic lagoons for the treatment of industrial wastes is not known. A survey by Porges (25) in 1962 revealed that 197 anaerobic lagoons were in service at that time with the leading users being the canning industry with 79, meat and poultry 29, paper 18, textile 17, and sugar 16. The information presented would indicate that many of these anaerobic lagoons were overloaded aerobic ponds. Unfortunately, the literature provides only a limited number of accounts of the operations of anaerobic lagoons or the effectiveness of the treatment provided.

A summary of operating data for representative anaerobic lagoons treating industrial wastewaters is presented in Table 8. Variation has existed in the lagoon designs serving particular industries to compensate for a wide variety of waste characteristics and local climatic factors. Not all of the anaerobic lagoons have operated nuisance free.

The effectiveness of anaerobic lagooning of meat processing wastes has been well established. BOD removal efficiencies of 60-90% (Table 8) have been consistently demonstrated at organic loadings of 10-30 lbs of BOD/1000 cu ft of lagoon. Nuisance odors have generally not been a problem with meat wastes.

Meat processing wastes contain high concentrations of organic matter with BOD and suspended solids concentrations frequently in excess of 1000 mg/l. Pretreatment of meat processing wastes before discharge to anaerobic lagoons has been reported. These processes include primary sedimentation and grease recovery (3) or only grease removal (6)(9). Anaerobic lagoons have, however, effectively treated meat waste without pretreatment. Removals in excess of 90% have been reported for anaerobic lagoons receiving the unsegregated wastes from small slaughterhouses including blood and paunch manure(4).

The extent of accumulation of solids in anaerobic lagoons will vary considerably depending primarily upon the quantity and characteristics of the wastewater, the degree of destruction of the organic material by digestion and the concentration of solids carried with the effluent. Loehr (17) has provided tables to estimate the approximate time required for anaerobic lagoons to fill with nonbiodegradable solids. Solids have been found to accumulate at various rates in anaerobic lagoons treating meat wastes. The shallow ponds receiving paunch manure have required solids removal after a couple of years. With preliminary treatment, the solids buildup on the lagoon bottom is reported to be extremely slow (8)(31); however, in one case, a grease scum layer 1.6 ft deep reduced the lagoon volume and detention time by 17.5%(31).

Enders _et al_. (8) have studied the solids concentrations at various depths in a 15 ft deep anaerobic lagoon receiving slaughterhouse waste through an inlet near the bottom. The bottom 5-6 feet of the lagoon was found to contain a relatively concentrated sludge of 3 to 4% volatile solids. Above a

Table 8

Operating Data for Anaerobic Lagoons
Treating Industrial Wastewaters

Investigator/s Reference	Type of Waste	BOD Concentration-mg/l		BOD Removal %	Bod Loading lbs/1000 ft^3	Temperture °C
		Influent	Effluent			
Sollo (3)	Meat	1096	159	85.5		
Rollag & Dornbush (6)	Meat	940	458	58.2	16.1	25
Enders et al. (8)	Meat	1880	350	87	31.4	22-27
Wymore & White (9)	Meat	----	670	64.9	12.7	----
Hester & McClurg (26)	Meat	1703	122	92.8	9.0	24
Dietz et al. (7)	Meat	3000	300	90	---	25-26
Coerver (14)	Meat	2070	158	92.4	---	----
Parker (27)	Fruit	3380	445	86.8	630*	
	Tomato	728	163	77.6	628*	
	Citrus	939	241	74.4	662*	

(continued) Table 8

Investigator/s Reference	Type of Waste	BOD Concentration-mg/l		BOD Removal	BOD Loading lbs/1000 ft^3	Temperature °C
		Influent	Effluent			
Canham (32)(28)	Tomato	982	599	39.8	33.9	14-24
	Peas	1444	---	37	23.2	-----
	Corn	2164	---	47.5	15.9	-----
Howe *et al.* (29)	Chemical & Fermentation	10,000	2000-	60-80	---	5,10,15
Cooper *et al.* (19)	Rendering	1870	----	88	228*	19-36
McIntosh & McGeorge (30)	Corn Products	<4000	----	58	---	21
			----	92	---	38
Loehr (16)	Milking Parlor	1030	160	85	9	29
		1030	830	20	9	2

*lb BOD/acre/day

well-defined sludge blanket, volatile solids concentrations were less than 0.1%. Placement of the lagoon outlet 2 ft from the surface resulted in the raw wastewater passing up through the concentrated sludge blanket. Average removals for the surveys during the summer were 87% for BOD, 76% for volatile solids and 78% for COD. Removal efficiencies decreased substantially when higher than average influent flows occurred.

Recirculation of sludge solids was provided at an anaerobic lagoon treating packing house wastes in order to simulate an anaerobic contact process (26). Sludge with 2% solids was returned from the center of the bottom of the anaerobic lagoons and recycled with inflow at a ratio of 1:1 to a manhole preceeding a corner inlet near the surface of the lagoon. Lagoon temperatures ranged from 66-90°F and BOD removal efficiencies for a four-year period averaged 79.6%. A heavy sludge bank accumulated near the inlet of the lagoon.

Anaerobic lagoons treating slaughterhouse wastes have been reported to operate without nuisance odors. Grease and solids form a scum crust on the lagoon surface providing insulation and excluding oxygen from the lagoon contents. Coerver (4) reported that the shallow anaerobic ponds in Louisiana were odor free only after the crust was formed on the shallow ponds and suggested that paunch manure was advantageous to the formation of an adequate crust.

The high temperatures of meat slaughtering wastes are probably a major factor contributing to the success of anaerobic lagoon treatment in the more severe climates. With detention periods of 3 to 5 days 80% removals were reported for a lagoon system in Canada (10). After a thick scum crust had developed on a lagoon in Minnesota effluent temperatures averaged 87°F for a weekly period even though average air temperatures were -2°F (31).

Cannery waste treatment with anaerobic lagoons has been reported to be successful in several instances. Canham (28) reported, however, that cannery waste lagoon systems have generally been designed to serve as storage areas for a seasons wastes. Odor remains a problem with cannery lagoons.

Canham (32) reported the successful use of anaerobic digestion of mixed tomato and lima bean wastes in a lagoon located in Indiana. An abundance of sludge from a previous canning season was available for seed and a single raft-mounted mixer was used to create movement of the lagoon contents and mixing with the raw wastes. Lagoon temperatures ranged from 64 to 84°F and lagoon pH from 5.4-7.2. BOD reduction was 39.8% with an average loading of 33.9 lb BOD/1000 cu ft and an average detention time of 2.54 days. The system operated odor free throughout the season.

Subsequent studies that were made in 1950-53 of anaerobic lagoons treating wastewaters from canning of peas and corn were reported by Canham (28). The anaerobic lagoon was double the size reported for the tomato wastes and four mixers were employed. Digested sludge (175,000 gal) was added to seed the lagoon. BOD loadings ranged from 12.5 to 27.8 lb/1000 cu ft and removals from 22 to 69%. A severe odor problem in the digester led to the addition of sodium nitrate for odor control. The blades of one mixer were adjusted so that it agitated the lagoon surface creating a "Semianaerobic and semiaerobic digester," a condition considered advantageous at the time for odor control. Based on the necessity of methane formation for odor-free anaerobic lagoon performance as stated by Oswald (23), the increased mixing to induce oxygen into the system may have been detrimental.

Parker (27), following pilot studies, utilized anaerobic lagoons for the successful treatment of cannery wastes in Australia. Fruit canning wastes (apricots, peaches and pears) were mixed with sewage treatment plant effluent that supplied nitrogen and phosphorus and with digester sludge to supply methane organisms before discharge to the lagoons. In another case, lime was added to tomato and citrus wastes to maintain a pH above 7.0 before lagooning in a similar manner. Oxidation ditches were used to treat the anaerobic lagoon effluent. The anaerobic lagoons were found to operate odor-free when BOD loadings were 600 lbs/acre/day for fruit wastes, 400 lbs/acre/day for tomato processing wastes and 200 lbs/acre/day for citrus wastes. BOD removals were 75 to 80%. Sludge accumulations have not been a problem with a maximum depth of 9 inches measured adjacent to the inlet after 5 years. A considerable cost advantage was shown for the anaerobic lagoon - oxidation ditch system in comparison with aerobic lagoon or spray irrigation systems.

Gilde (33) reported that a 15 ft deep anaerobic lagoon with a four day detention and a design loading of 12 lbs BOD/1000 cu ft/day accomplished a 65% BOD reduction on a cannery waste. The lagoons were installed to alleviate solids deposition problems and associated odors in the aerobic lagoons that had previously received the cannery wastes.

Cooper et al. (19) reported results indicating that anaerobic lagooning has been successfully applied to wastewaters from a rendering plant, a hide washing plant and a poultry (manure) unit. The presence of purple sulfur bacteria were noted to contribute to the odor free operation of these lagoons.

An 88% BOD removal was reported for the anaerobic lagoon, (7 ft deep with 160 days detention) treating the rendering wastes at a BOD loading of 228 lb/acre/day. Gas production was measured to range as high as 2400 cu ft/acre/day with 70.3% methane. Pilot plant studies were strongly suggested prior to the design of anaerobic ponds because of the lack of fundamental knowledge of the design parameters involved.

Anaerobic lagooning has also been applied to wastewaters from the industrial chemical and fermentation processes (29). Pilot studies revealed that BOD removals of 60 to 80% could be achieved at temperatures ranging from 22°C to 5°C. Volatile acids, alkalinity and BOD concentrations were all observed to increase with each successive drop in temperature.

Starch refining wastes that had temperatures ranging from 91-114°F have been found particularly amenable to treatment with anaerobic lagoons. McIntosh and McGeorge (30) reported that an anaerobic cell accomplished BOD reductions from 58% in winter to 92% in summer at lagoon temperatures of 60°F and 90°F respectively. The pH of the raw starch wastes was adjusted from 4.5 to 9-11 with caustic soda and a recirculation system provided continuous seeding of the influent. Three-inch plastic foam rafts were used to insulate a portio of the anaerobic cell and to maintain higher lagoon temperatures. Solids accumulations near the inlet were removed with a dragline. Odor problems encountered during the early stages of operation were combatted with ammonia nitrate feed.

Milking parlor waste treatment in anaerobic lagoons has been reported to be satisfactory by Loehr and Ruf (16). At a loading of 9 lb BOD/day/1000 cu ft, reductions were 85% for the summer, with liquid temperatures at 85°F, and 20% for the winter with liquid temperatures of 35°F. Solids were settled out during the winter period but digestion was not active until spring. When solids that had accumulated in the lagoon were removed in the early winter, the performance was affected. Decreased alkalinity and increased volatile acids concentrations occurred in the bottom sludges; however, the lagoon recovered in the summer. A general decrease in efficiency was noted as the winter progressed.

Swine manure lagoons were studied in South Dakota to determine their ability to dispose of solids in an odor free manner (34). Active digestion in lagoons to the extent that ebullition of gases created a mixing action resulted in odor-free lagoons. Supernatant of an odor-free lagoon was found to have a volatile acids concentration equal to about 15-30% of the alkalinity whereas volatile acids concentrations always exceeded the alkalinity for highly odorous lagoons. The lagoons did not have an effluent. Lagoons which had developed active decomposition during the previous summer maintained sufficient "seed" material through the winter to avoid offensive odors the following spring. Similar observations have been made for a poultry manure lagoon. (11).

Effluent Quality and Quality Criteria

Anaerobic lagoons have not been considered adequate as a complete wastewater treatment unit except when the volume of flow is so small that evaporation and seepage eliminates the necessity of an effluent. For example, effluents from anaerobic lagoons treating feedlot wastes could pollute a receiving body of water (35). The effluents are high in oxygen demanding materials and solids. As a result, designers have found it necessary for the effluent to be discharged to secondary biological treatment units usually oxidation or stabilization lagoons. Secondary treatment has also been satisfactorily provided with activated sludge units (7) and an oxidation ditch. (27).

The quality of effluent from an anaerobic lagoon is dependent to a considerable extent on the wastewater being treated. High strength wastes might be expected to yield potent effluents. BOD concentrations of 100 to 300 mg/l occur in anaerobic lagoon effluents treating municipal wastewaters (Table 8) with somewhat higher concentrations resulting with industrial wastewaters (Table 8). Experience has shown that effluent BOD concentrations will probably range from 40 to 70% of inflow BOD for municipal wastewaters and 10 to 40% for industrial wastewaters.

Digestion of solids in anaerobic lagoons accomplishes considerable stabilization of the organic matter; however, the nutrient elements of nitrogen and phosphorus are released to the lagoon liquid. For example, with a slaughterhouse waste, a 30 mg/l organic nitrogen reduction through the anaerobic lagoon was accompanied by an increase of 30 mg/l in ammonia (6). Thus, the effluent for anaerobic lagoons usually contains high concentration of nutrient chemicals such as nitrogen and phosphorus which are readily available to support biological growth in subsequent secondary treatment units.

Theory

The anaerobic lagoon might be considered as analogous to the septic tank. During the two to ten day detention, the solids entering the lagoon with the wastewater either settle to the bottom as sludge or rise to the top as scum. This solids separation would account for a removal efficiency of 25 to 40% on a purely physical basis. Early investigators, however, recognized that anaerobic lagoons provided removals in excess of that accounted for by simple sedimentation.

Parker et al. (1) in 1950 reported the results of early studies with anaerobic lagoons explaining:

> The high efficiency of the anaerobic lagoon in removing BOD is dependent on the development of digestion in the sludge layer. Organic matter is converted to methane and carbon dioxide under anaerobic conditions and the gassing of the sludge layer seeds the sewage flowing over it.

In this manner, the organics remaining in the supernatant were subjected to treatment.

The underlying treatment mechanism of the anaerobic lagoon is anaerobic digestion, a process which has been subjected to intensive investigation to unravel the complex reactions and to understand the limitations involved. Review of several sources (36)(37) would provide extensive coverage of the theory and fundamental factors that may be related to the anaerobic lagoon.

Digestion of complex organic material in the anaerobic environment can be simplified and summarily described as occurring in two sequential stages. In the initial state, the complex materials such as carbohydrates, proteins, and fats are biologically converted and fragmented by processes of hydrolysis and fermentation to the simpler organic end products including aldehydes and alcohols but principally fatty organic acids. For this reason, the mixed groups of facultative and anaerobic organisms that accomplish this initial conversion, are commonly termed "acid formers." The organisms derive small amounts of energy from the reactions which in turn is converted to bacterial cell growth. Relatively little stabilization of organic matter as would be measured by BOD or COD reduction occurs in this initial stage of the conversion. The organic matter simply undergoes an antecedent breakdown in preparation for the second stage reaction.

The methane formation stage of digestion proceeds, with a favorable environment, where the first stage ends. Organic acids produced during the initial breakdown are converted by the methane-forming organisms to gaseous end products, principally methane and carbon dioxide. It is with this second conversion that the waste stabilization occurs, being directly proportional to the methane produced (38). The gaseous end products released in the final stage of organic digestion may escape from the liquid as in the case of hydrogen sulfide, carbon dioxide and methane, or remain in the liquid to serve as a buffering system as with ammonia and carbon dioxide. The maintenance of conditions to accomplish a proper balance between the two groups of organisms is essential to prevent the development of low pH conditions by the acid formers and to accomplish relatively nuisance free treatment in the anaerobic lagoon.

The application of the simplified theory to the design of an anaerobic biological wastewater treatment system, such as an anaerobic lagoon, must depend upon the proper relationships between the organic matter in the wastes, the microorganisms which can metabolize the organic matter, the generation time of the microorganism, the temperature of the treatment system, the wastewater retention period, the pH, the alkalinity, the nutrient elements, and proper mixing (39).

It is generally recognized that the organisms involved in methane formation are more vulnerable to adverse environmental factors such as low temperature or low pH and particularly the presence of dissolved oxygen. Table 9 contains the range of values as listed by Oswald (23) for environmental factors at which the organic acid formation and methane fermentation reactions may be useful for waste treatment in ponds. As has been noted previously, design of anaerobic lagoons to obtain the conditions conducive to continuous methane formation would, in theory, be most desirable.

Design and Operation Modifications

Several variations in the design and operation of anaerobic lagoons appear to have merit in that they probably have improved removal efficiency or solved operation problems. The development of an environment which will result in adequate methane formation should apparently be the major objective in order that odor nuisances will be avoided.

Lagoon temperature, to a large extent a climatic factor, plays an important part in the success of anaerobic lagoons. Nearly all anaerobic ponds have been observed to function better during the summer. In Australia and California adequate temperatures in excess of 15°C can be maintained with the asssstance of solar radiation throughout most of the year with lagoon depths of about 3 feet. In Canada, where the major source of heat would probably be the incoming wastes, deep ponds with short detention are found to be more satisfactory. In Israel (40) extra-deep ponds (5 meters) were found to develop thermal gradients which would

Table 9

Required Conditions or Levels for Indicated Biological Reaction in Ponds (23)

Environmental Factors	Organic Acid Formation			Methane Fermentation		
	Min.	Opt.	Max.	Min.	Opt.	Max.
Population	Heterotrophs facultative			Mesophilic bacteria		
(No. per ml.)	10^8	10^{10}	10^{12}		Unknown	
Nutrients	Carbohydrates, Protein, fat			Organic acids, Alcohols		
Oxygen (mg/l)	0	0	1	0 0	0	0
Time (days)		5-10			40-120	
Initial/Active	1/6	1/12	1	10	40	100+
Temperature, °C	4	25	40	15	32	40
pH	4.3	6.5	7.5	6.8	7.0	7.2
Alkalinity (mg/l)		Unknown		500	2000	-
Antecedent reactions	Organic synthesis			Organic acid formation		
Competitive reactions	Oxidation			Oxidation		
Predators		Unknown			Unknown	
Toxic substances	Salts, heavy metals			Oxygen, copper, salt, chromium heavy metals		
Energy source	Nutrients			Nutrients		
Redox potential $E_n$mv	-0.1	-	+0.2	-0.10	-0.5	-

in effect result in a facultative pond layer floating over an anaerobic layer; however, temperatures remained above 15°C in all layers throughout the year.

Oswald (23) has suggested that the development of thermal layers makes possible recirculation from the final aerobic pond to the primary anaerobic lagoon for the purpose of eliminating odors. If the water temperature of the aerobic pond is warmer than the water on the bottom of an anaerobic pond, a layer with dissolved oxygen will reportedly overlay the anaerobic pond eliminating sulfide odors. The possible instrusion of oxygen into the anaerobic zone where it would be detrimental to methane formation is avoided solely by the thermal density layers.

Oswald has suggested that special designs of the anaerobic lagoon near the inlet to create a special sludge digestion chamber have proved advantageous. A conical-shaped enlargement with increased depth surrounding the inlet was one of the designs suggested. Another design would employ a submerged baffle to surround the digestion zone into which the influent was discharged. These designs had been used to prevent intrustion of oxygen into the digesting sludge when recirculation from the aerobic ponds for odor control was included in the design.

Obtaining intimate contact between the raw influent and active methane forming organisms in the lagoon may be expected to result in increased BOD removals and possible less odor problems. Parker and Skerry (24) have suggested that shallow lagoons bring the deposited sludge closer to the supernatent where gas evolution would achieve mixing. Dornbush and Andersen (11) stressed the importance of the mixing that occurred in animal manure lagoons with gas bubbling action and used a pump to artificially mix sludge banks deposited on the bottom of a poultry lagoon for the purpose of eliminating odors.

The designs suggested by Oswald to create a digestion chamber near the lagoon inlet would be expected to accomplish mixing. Enders et al. (8) reported that for a lagoon receiving slaughterhouse wastes a sludge blanket developed to a depth of about 5 ft. As a result the placement of the inlet near the bottom would be expected to accomplish the desired mixing. At other lagoons recirculation of sludge to the inlet accomplished the mixing (3)(26). Canham (28) has reported improved results with a single raft-mounted mixer placed near the inlet of a cannery waste lagoon; however, a later installation with four mixers experienced odor problems.

Recirculation of supernatent has also been used to seed incoming wastes. Over 200,000 gallons of effluent were returned daily to innoculate the incoming wastewater at a corn starch plant (30). Recirculation of supernatent from a second anaerobic lagoon in series at a rate of 1.3 to 1 for the raw wastes resulted in a 5-6% increase in BOD removal efficiency in two anaerobic lagoons treating slaughterhouse wastes (31).

In northern climates where for prolonged periods the major source of heat may be the incoming wastes, floating covers have been used for anaerobic lagoons. A plastic foam raft, 3 inches thick, was installed to cover 30,000 sq ft of an anaerobic lagoon treating corn products wastes (30). The insulating value of the plastic foam was sufficient to cause snow to remain on top of the cover during the winter with liquid temperatures of 85°F underneath (41). A similar plastic foam cover has been used to prevent heat loss from a packinghouse waste lagoon (7).

With meat packing wastes a natural scum cover forms on anaerobic lagoons as a result of grease and paunch manure in the waste. This natural cover proved to be adequate insulation to prevent the lagoon temperatures from dropping below 75°F in Minnesota, (6) although preliminary design had indicated that external heat would be required and a support column had been constructed in the lagoon for an underwater gas-fired heater. The heater was never installed. Subsequent studies on this anaerobic lagoon (31) determined that the grease scum layer had a thermal conductivity of 0.38 BTU/hour-°F-ft. Snow would accumulate on the surface of the scum crust.

Covers on anaerobic lagoons may be beneficial for the prevention of odors. Coerver (4)(5) reported that anaerobic lagoons treating slaughterhouse wastes became nuisance free only after a crust had formed over the lagoon surface. It would appear that the scum covers or crusts would be beneficial in preventing a condition more favorable for methane forming bacteria. This would appear to be particularly important for the shallow anaerobic ponds described by Coerver.

The scum crusts and sludge in an anaerobic lagoon may be expected to eventually accumulate to considerable depths and require removal. In order to accomodate the use of a dragline for solids removal, Coerver (4) suggested that anaerobic lagoons be designed to be long and narrow with the length at least three times the width. The use of pumps also proved satisfactory for removal of sludge accumulations (3)(30). Sludge removed from the lagoons dried without the creation of a nuisance.

When the grease and paunch cover of an anaerobic lagoon serving packing plants in Edmonton, Canada became 5 to 6 ft in thickness, removal was accomplished by burning resulting in a saving of several thousand dollars (42). The scum was sprayed with fuel oil and kerosene and ignited with a gasoline flame. The resulting smoke pall was reported to be light in density and to have dissipated within 1/2 mile from the lagoons; as a result there were no complaints. The burning action continued for a considerable time surviving two high intensity rain storms and several snowfalls.

The literature contains accounts of start-up procedures that have avoided a prolonged period of nuisance odors when an anaerobic lagoon is put into service (6)(17). These procedures approach those used for starting a sewage sludge digester including provisions for an adequate population of microorganisms (methane formers) suitable to complete the digestion and consideration for the major environmental factors of temperature and pH.

Summer would be the preferable start-up time for an anaerobic lagoon when the contents can be maintained at temperatures well in excess of the suggested 15°C minimum. Temperatures approaching 35°C would be preferable. A high initial population of methane formers must be provided with an initial seeding of sludge from a municipal sludge digester or similar source undergoing active anaerobic digestion. Lime feed may be used to control the pH in the lagoons to the desired range of 6.8 to 7.2.

Research Needs

Temperature - Thermal considerations should receive greater attention in the design of anaerobic lagoons particularly in the colder climates. Primary sources of incoming heat to the lagoon include solar energy and heat transmitted with the incoming waste. If heat sources are insufficient to compensate for the heat losses that may occur via the effluent and through conduction, convection, evaporation and radiation, measures to limit these losses would be in order. These measures might include shortening the detention time of the lagoon, limiting recirculation, or utilizing insulating lagoon covers either natural or artificial. The measures would be successful only if the total heat input of the incoming waste is expected to maintain an adequate lagoon temperature.

Limitations in the activity of the methane formers at 15°C would appear to establish the lower temperature limit that must be maintained throughout the lagoon, particularly in the sludge deposits on the bottom. When heat input from wastes appears insufficient to maintain this 15°C temperature, it may be possible to separate waste streams on a basis of temperature and divert cold waste streams to secondary units after sedimentation. Heat input by artificial means could also be used.

Lagoons located in Australia and California rely primarily on solor heat to maintain adequate temperatures, consequently, shallow ponds with large surface areas have proved successful even with relatively dilute municipal wastes. In Canada deeper ponds with less surface area exposed to the atmosphere have proven more satisfactory for treatment of municipal wastewater although odor problems have been encountered.

These lagoon adaptations signal the need for measuring the total heat input in future studies which evaluate loading and treatment efficiencies of anaerobic lagoons. Temperature measurements in bottom sludge accumulations as well as in the overlying supernatent would determine if minimum acceptable temperatures were being maintained throughout the entire system. There appears to be a serious lack of information on tht total temperature environment at field installations.

Loading and Detention Time - The organic loading parameter is widely used as a basis for the design of anaerobic lagoons. Naturally this term may be confusing because it has been expressed in terms of area as lbs BOD/acre/day or in terms of volume as lbs BOD/1000 cu ft/day or lbs volatile solids/1000 cu ft/day etc. Describing the organic loading term as a function of area would not appear to be adequate because the digestion process and hence the stabilization of the wastes may take place throughout the entire depth of the wastes lagoon. However, the loading rates can be compared when the lagoon depth is known. For example, an anaerobic lagoon 3 feet deep with a BOD loading of 600 lbs/acre/day would have a BOD loading of 4.6 lbs/1000 cu ft/day. Nevertheless, organic loading is not an enitrely satisfactory expression because it does not consider detention time.

The computation of organic loading considers both wastewater flow and wastewater concentration and an increase in either flow or concentration of the influent would increase the organic loading of the anaerobic lagoon. However, the lagoon detention time will be influenced only by changes in flow. The approximate variation of treatment efficiency of the digestion process with detention time is known - treatment efficiency increases with detention time but at a decreasing rate. Consequently, for a given organic loading, a higher influent concentration would be expected to result in greater removal efficiency because of the increased detention time. This is borne out by the high removals attained by anaerobic lagoons with high strength industrial wastes even at higher organic loadings.

The nature of the organics either soluble or settleable that would make up the organic loading would, however, be of particular significance with respect to the efficiency of anaerobic lagoons. The settleable portion would be easily retained for long periods in the lagoon even though conditions for complete stabilization may not exist. This would explain substantial BOD removals in the winter when methane production would be retarded. The solids would merely be stored as sludge until conditions more favorable to digestion occur and the stabilization takes place. The soluble organics, however, would be in transit continually and as a result the detention time of the anaerobic unit would determine the extent of stabilization.

At the present time, there is little information available concerning the nature of the BOD that remains in the effluent of anaerobic lagoons. With anaerobic contact and sludge digestion systems, the major portion of the BOD in the effluent is attributed to the solids which are carried from the systems. This, however, has not been demonstrated with anaerobic lagoons. If, for instance, a large portion of the effluent BOD is of a soluble nature, measures including recirculation or mixing as well as increasing the detention time may be required to improve the efficiency. These measures would naturally be in addition to maintaining an overall satisfactory environment for methane formation.

Sludge Accumulations and Odors - Numerous accounts of complaints of odors from anaerobic lagoons of all types would seem to deter their adoption by all but the most adventurous. Equally frequent reports of successful operation with high removal efficiencies at low costs and without odor complaints create a dilemma for those who must make the final decisions. A ray of hope seems to be emerging from the multitude of observations and reports. Meager information seems to point the accusing finger at sludge deposits accumulated on the bottom of lagoons as being a major source of noisome odors.

It is reasonable to assume that solids settling from wastewaters in lagoons will begin to undergo decomposition depending on the total environment. With low water temperatures or an inadequate population of methane formers the first stage of digestion, that of acid formation, will proceed within the sludge accumulations because of the ability of the "acid formers" to function in the less favorable environment. The resulting organic acids would quickly exceed the limited buffering within the sludge accumulations and the pH would begin to drop to further limit the performance of the methane formers.

Organic acids would be expected to accumulate and an acid sludge bank or "pocket" would develop. It is hypothesized that these acid sludge accumulations are a major source of odors in lagoons. Odors will be produced in the acid sludge until this localized "pickling" environment is altered, either through dispersion by mixing, pH adjustment, or development of an adequate population of methane formers to break down the acids.

The numerous reports of malodors after anaerobic lagoons had been initially put into service, and the success usually encountered in avoiding odors when recently constructed lagoons were seeded with an active sludge would tend to support this hypothesis. Success reported in eliminating vile odors by artificially mixing and accumulated solids in a poultry lagoon with a pump provides additional substantiation.

Odors in the spring of the year have come to be expected in northern climates. During long severe winters, after lagoon temperatures have dropped and digestion has ceased, solids from raw incoming wastewaters settle to form a blanket of raw sludge over the "seed" sludge remaining on the lagoon bottom from the previous year. Odors are probably produced in this overlaying blanket when the initial organic breakdown results in an acid sludge. Malodors will continue to occur until favorable temperatures reach the active sludge from the previous year and "gassing" begins. When sufficient gas is produced in the lower layer to result in a bubbling action, the self induced mixing will break up the acid sludge layer resulting in an adjustment of pH and a rapid correction of the odor problem.

More information on the actual conditions that exist in sludge layers of lagoons that are experiencing extreme odor problems is needed. In situ measurement of sludge temperature, pH, and ORP combined with the results of analyses of sludge samples for volatile acids, alkalinity and hydrogen sulfide, would greatly assist in determining the significance of solids as the major source of odors. Once the major source is established, corrective measures may be devised.

In summary, research activities with anaerobic lagoons should be directed at more clearly defining:

(1) the thermal environment throughout lagoons,
(2) the natural of the organics in both the lagoon influent and effluent,
(3) the actual detention time of organics within the lagoon, and
(4) the relative importance of sludge accumulations as a major source of nuisance odors.

With this information, design criteria that would result in a satisfactory waste-stabilizing environment within lagoons can be established.

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SECTION VII

ACKNOWLEDGEMENTS

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The support of the Missouri Basin Engineering Health Council under the Chairmanship of Mr. A. E. Williamson, Director, Wyoming Division of Sanitary Engineering is gratefully acknowledged.

The assistance for this project by the Water Quality Office, Environmental Protection Agency, and the patient encouragement provided by Mr. Otmar Olsen, the Grant Project Officer, is acknowledged with sincere thanks.

SECTION VIII

GLOSSARY

Acid Formers - Bacteria which metabolise organic matter in the absence of dissolved oxygen with the formation of organic acids.

Active Microbial Mass - The living fraction of biological sludges.

Aerated Lagoons - Large ponds that use mechanical aeration for oxygen transfer.

Aerated Oxidation Pond - A large wastewater treatment pond employing diffused aeration systems for mixing as well as supplemental aeration.

Aerobic Bacteria - Single cellular, non-photosynthetic plant cells which grow in the presence of dissolved oxygen.

Air Gun - A tube type aeration system employing a special air chamber which discharges a slug of air periodically like a gun.

Algae - Microscopic plants which carry out photosynthesis in the presence of sunlight.

Alpha Coefficient - An oxygen transfer factor determined by the chemical composition of the wastewaters and affecting the rate of transfer of oxygen from the gas phase to the liquid phase.

Anaerobic Lagoons - A deep pond designed to operate as a combined sedimentation unit and an anaerobic digester.

Anionic Polyelectrolyte - Large complex organic molecules which form insoluble compounds in water with a negative electrical charge.

Beta Coefficient - An oxygen transfer factor determined by the soluble chemical composition of the wastewaters and affecting the saturation of oxygen in the liquid phase.

BOD (Biochemical Oxygen Demand) - The quantity of oxygen utilized by microorganisms in the stabilization of organic matter at 20°C over a period of time.

Cage Rotor - A mechanical aerator employing a number of flat metal plates spaced at regular intervals along horizontal rods suspended between two circular end plates and rotated along a horizontal axis at a speed of less than 100 RPM.

Carbon Filter - A filter of activated carbon used to adsorb organic matter from water.

Cationic Polyelectrolytes - Large complex organic molecules which form insoluble compounds in water with a positive electrical charge.

Chemical Precipitation - The destabilization and aggregation of colloidal and finely divided suspended matter by the addition of a floc forming chemical.

Chlorinated Hydrocarbons - Organic compounds of carbon, hydrogen and chlorine.

Chlorination - The process of adding chlorine to water or wastewaters.

Ciliated Protozoa - Single cell microscopic animals with cilia for motility.

COD (Chemical Oxygen Demand)- A measure of the oxygen consuming capacity of wastewaters obtained by a 2 hr sulfuric acid-dichromate refluxing.

Coliform Bacteria - Gram negative, non-sporing forming bacilli that ferment lactose with the production of acid and gas and are found primarily in the intestines of man and animals.

Complete Mixing - A high degree of turbulent mixing in which the fluid turnover is approximately one to two minutes.

Crustaceans - Aquatic anthropods having a body covered with a hard shell or crust.

Denitrification - The process of microbial nitrate reduction with the production of nitrogen gas.

Diffused Aeration - Aeration produced in a liquid by passing compressed air through a diffuser.

Endogenous Mass - The mass of microbes remaining after endogenous respiration had metabolised all of the biodegradable cellular material.

Endogenous Respiration - The microbial metabolism of intracellular tissue.

Enteric Pathogens - Disease producing microorganisms that normally grow in the intestines of warm blooded animals.

Facultative Aerated Lagoon - A large wastewater treatment pond employing mechanical surface aerators which produces aerobic zones around the aerators and allow solids to settle out in quiescent areas.

Fecal Coliforms - Coliform bacteria that are derived from the intestinal tract of man and warm blooded animals.

Fungi - Non-photosynthetic, multicellular microscopic plants that grow in water.

Inert Inorganic Mass - Inorganic suspended solids in wastewaters, which remain insoluble.

Inert Organic Mass - Organic suspended solids in wastewaters which are resistent to biological degradation in conventional biotreatment systems.

Microorganisms - Tiny plant and animal organisms which can be observed only by use of a microscope.

Microstraining - Process of removing suspended particles from water by filtering through a woven metal cloth of a fine mesh.

MPN (Most Probably Number) - The number of organisms per unit volume based on statistical analysis normally used for coliform bacteria.

Natural Purification - The stabilization of organic or inorganic compounds by the microorganisms normally found in nature.

Nitrification - Aerobic microbial oxidation of ammonia to nitrites and then to nitrates.

Non-Biodegradable Suspended Solids - Organic suspended solids that are not readily metabolised by microorganisms.

Oxidation Ditch - A modification of activated sludge which utilizes a mechanical aerator to move the mixed liquor around a circular ditch.

Oxidation Ponds - Large ponds of shallow depth with long fluid retention times which utilize symbiosis between bacteria and algae.

Percolation - The flow of liquid downward through a filtering medium.

Photosynthesis - The process of converting carbon dioxide, water and inorganic salts into organic matter with energy from light with chlorophyll as a catalyst.

Primary Sedimentation - The first stage of wastewater treatment consisting of gravity separation of suspended solids.

Protoplasm - Cellular tissue within the microbial cell wall.

Raw Sewage - Untreated wastewaters.

Rock Filter - A submerged filter utilizing rocks as a media for removing algae from oxidation ponds.

Rotifers - Multicellular, microscopic animals with cilia that resemble rotating wheels when in motion.

Sand Filtration - A filter composed of graded sand designed to remove small suspended solids.

Spray Irrigation - The spreading of wastewaters on agricultural land by spraying.

Supernatant - The liquid standing above a sediment or precipitate.

Surface Aerators - Mechanical aerators which dissolve oxygen in water by pumping the water into the air.

Suspended Solids - Solids in suspension in water which can be removed by standard laboratory filtration techniques.

Symbiosis - Two organisms living together with the production of a greater reaction than the organisms alone.

Turbidity - Finely dispersed suspended solids in water.

Virus - Tiny microscopic mucleo protein particles which multiply within specific hosts, creating a disease within the host.

Waste Treatment Lagoons - Large ponds used for wastewater treatment.

Zooplankton - Microscopic animals in water.

1 Accession Number	2 Subject Field & Group	
W		**SELECTED WATER RESOURCES ABSTRACTS** **INPUT TRANSACTION FORM**

5 *Organization*
Missouri Basin Engineering Health Council

6 *Title*
Waste Treatment Lagoons - State of the Art

10 *Author(s)*
Ross E. McKinney
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16 *Project Designation*
Project # 17090EHX

21 *Note*

22 *Citation*

23 *Descriptors (Starred First)*
Wastewater Treatment*, Water Pollution Control*, Aerated Lagoons*, Anaerobic Lagoons*, Oxidation Ponds*, Sewage Treatment, Industrial Wastewater Treatment.

25 *Identifiers (Starred First)*
Operation of Wastewater Treatment Lagoons*, Design of Wastewater Treatment Lagoons*, Concepts of Wastewater Treatment Lagoons, Field Data from Wastewater Treatment Lagoons.

27 *Abstract*

This report compiles the State of the Art for wastewater treatment lagoons as existing in 1970 based upon the published literature and field evaluations.

Wastewater treatment lagoons comprise oxidation ponds, aerated lagoons, and anaerobic lagoons. Oxidation ponds are large, shallow ponds designed to treat domestic sewage from small communities or subdivisions. Aerated lagoons use mechanical aeration devices to supply oxygen for the microbes for treating domestic sewage and industrial wastes. Anaerobic lagoons are designed to treat primarily strong industrail wastes from meat processing industries.

The evaluation of current state of the art with biological theory offers new approaches for improving wastewater treatment lagoons.

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WR:102 (REV. JULY 1969)
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